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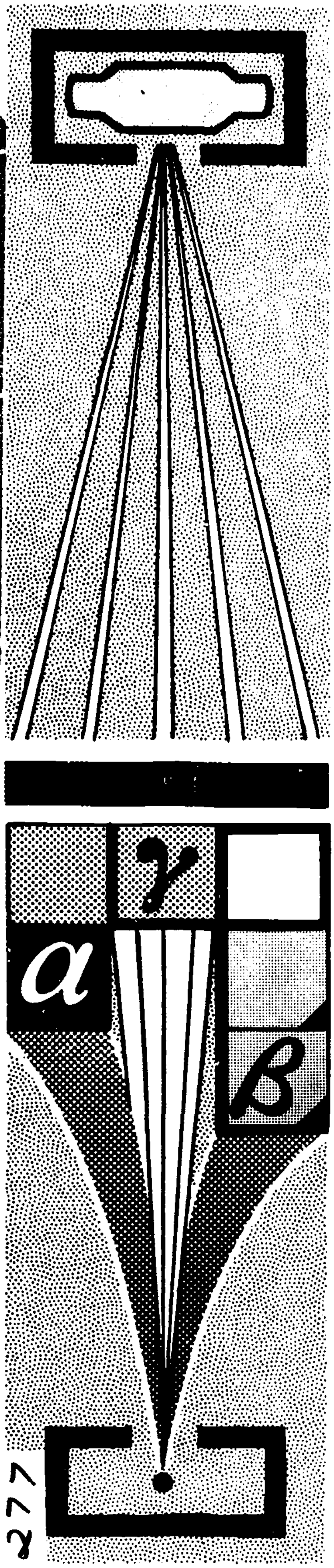
ABSTRACT

This is the first of a series of three instructor manuals in x-ray science and engineering and is produced as part of a project of Oregon State University's Bureau of Radiological Health. This manual, and the two companion manuals, have been tested in courses at Oregon State. These materials have been designed to serve as models for teaching and training programs in x-ray science and engineering. The manuals contain lecture outlines, laboratory exercises, and examinations. References, required equipment, and materials are listed. Each lecture and each laboratory exercise is essentially self-contained to permit other schools to select material on the basis of available time and equipment and the objectives of their instructional program. Equipment has been identified by model and manufacturer, but instructors may substitute equivalent equipment or alter course content to make use of available equipment. Fourteen lectures and eight laboratory exercises are presented in the first manual. Among other topics, these deal with the interaction of x-rays with matter, x-ray detection, chemical dosimetry, and correlation of exposure and absorbed dose. (PEB)



COURSE MANUAL for MACHINE SOURCES of X RAYS

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
FOOD AND DRUG ADMINISTRATION

TECHNICAL REPORTS

Technical reports of the Division of Medical Radiation Exposure, Bureau of Radiological Health, are available from the National Technical Information Service, Springfield, Va. 22151, when a PB number is indicated after the title. Microfiche copies are $0.95; prices for paper copies are indicated after the PB number. Bulk order prices are available from NTIS. The PB number should be cited when ordering. Some reports are also available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, as indicated after the title.

PHS 1559	Physical Survey Manual Dental X-ray (PB 183 019 $6)
PHS 1582	Radiation Protection Survey Report Manual (PB 183 018 $6)
PHS 1663	KWIC Index to the Journal of the Health Physics Society (1958-1966) (PB 176 092 $6)
PHS 1831	KWIC Index to the Journal of Nuclear Medicine (1960-1967) (PB 179 074 $6)
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MORP 68-5	The Use of Radium in Consumer Products (Supt. of Doc., GPO-40c) (PB 182 717 - microfiche only)
MORP 68-6	Preliminary Results of 5263 X-ray Protection Surveys of Facilities with Medical X-ray Equipment (1962-1967) (PB 180 526 - $6)
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MORP 68-10	Survey of the Use of Radionuclides in Medicine: Preliminary Report (Superseded by BRH/DMRE 70-1)

(continued on inside of back cover)

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BRH/DMRE Contract No. PH 86-65-92

ED 094952

COURSE MANUAL for MACHINE SOURCES of X RAYS

(O. S. U. Course GS-461)

Prepared by

The X-Ray Science and Engineering Laboratory
Oregon State University

under

Contract No. PH 86-65-92

Project Director:

E. Dale Trout, Director
X-Ray Science and Engineering Laboratory

Project Officer:

Arve H. Dahl, Acting Director
Division of Medical Radiation Exposure

JANUARY 1973

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
FOOD AND DRUG ADMINISTRATION
Bureau of Radiological Health
Rockville, Maryland 20852

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FOREWORD

The Bureau of Radiological Health implements a national program designed to reduce the exposure of man to hazardous ionizing and non-ionizing radiation.

Within the Bureau, the Division of Medical Radiation Exposure deals with 1) the reduction of unproductive ionizing radiation exposure of patients, workers and others exposed by the use of x rays and other machine-produced ionizing radiation, radioactive materials and radio-pharmaceuticals, and 2) the improvement of radiological "systems" and methodology in the healing arts. A number of projects and studies are aimed at assessing and minimizing radiation exposure in the healing arts and increasing efficiency in the use of radiation in clinical practice. Several projects are directed toward assessing and improving the qualifications of x-ray users in the healing arts.

Results of intramural and contractor projects of general interest are published as technical reports by the Division of Medical Radiation Exposure and distributed to State and local radiological health program personnel, Bureau technical staff and advisory committee members, university radiation safety officers, libraries and information services, industry, hospitals, laboratories, schools, the press and other interested individuals.

Contract reports on highly specialized topics are printed and distributed without editorial revision. Copies of both general interest and limited distribution reports may be purchased from the National Technical Information Service.

I encourage the readers of these reports to inform the Bureau of any omissions or errors. Your additional comments or requests for further information are also solicited.

John C. Villforth
Director
Bureau of Radiological Health

PREFACE

Since June 1965, Oregon State University's Department of General Science has been supported by the Bureau of Radiological Health through Contract No. PH 86-65-92 to organize, develop, and conduct a teaching and training program in x-ray science and engineering; and conduct related research, evaluation, and development activities. The project was made possible by the presence of the internationally recognized x-ray expert Dr. E. Dale Trout, Professor of Radiological Physics, who serves as the Project Director. The Assistant Project Director, John P. Kelley, Associate Professor, Department of General Science, is also a nationally recognized expert in the fundamentals and use of x-radiation.

This document, one of three instructor course manuals in x-ray science and engineering, is one of the project's significant contributions to radiological health. The three manuals have been tested in courses introduced into the university curriculum. They are presented in such form that they can be used as models for similar programs in other institutions.

It is appropriate to acknowledge other accomplishments of the project. The project has provided the following staff of the Bureau of Radiological Health with training and supervision in research, evaluation, and developmental work in x-ray science and engineering: Robert L. Elder, Sc.D.; Gregory J. Barone, Ph.D.; Bruce M. Burnett, M.S.; William S. Properzio, M.S.; Kenneth R. Envall, M.S.; Kenneth E. Weaver, M.S.; and Richard E. Gross, M.S.

Reports have been presented at professional meetings and published in the open scientific literature on evaluations of instruments used in x-ray measurements, methodology devised for evaluation of x-ray protective devices and materials, and methodology and instrumentation developed for measurement of x radiation. The project staff has also analyzed and reported to the Bureau regularly on related developments presented at annual meetings of the American College of Radiology, Radiological Society of North America, American Roentgen Ray Society, American Association of Physicists in Medicine, Health Physics Society, and the American Society of Radiologic Technologists.

A model complete x-ray instructional facility known as the X-Ray Science and Engineering Laboratory has been developed containing modern x-ray equipment, electronic and mechanical shops, classroom, office and support space.

Special acknowledgement is also made of the contract support provided to the project during the last 2 years by the National Institute for Occupational Safety and Health because of their need for research and development assistance on production of better quality radiographs for the coal miner pneumoconiosis control program. Acknowledgement is also made of past contributions in development of this project by Dr. Donald R. Chadwick, Mr. James G. Terrill, Jr., and Dr. Russell I. Pierce for the Bureau and by Dr. James H. Jensen, President of Oregon State University at the time the project was started, and Milosh Popovich, Dean of Administration for the University.

Arve H. Dahl

Arve H. Dahl, Project Officer

Acting Director
Division of Medical Radiation Exposure
Bureau of Radiological Health

CONTENTS

INTRODUCTION

There are three course manuals in this set. They are used by instructors in the Department of General Science at Oregon State University for planning and presenting a three-course sequence in x-ray science and engineering. The courses, which are offered each year, are open to both undergraduate and graduate students and must be taken in sequence. They are:

GS-461 Machine Sources of X Rays - Fall Term

GS-462 X-Ray Measurements - Winter Term

GS-463 X-Ray Applications - Spring Term

Each is a 3-credit-hour course and consists of two 1-hour lectures and one 3-hour laboratory each week. In the 6 years the course manuals have been used, classes have included students from programs in pre-dentistry, pre-medicine, pre-veterinary medicine, biology, oceanography, physics, engineering, chemistry, education, geology, pharmacy, physiology and agriculture. It is assumed that students will have no x-ray experience but that they will have had at least 1 year's work in college level physics and mathematics.

The course manuals contain lecture outlines, laboratory exercises, and examinations. References, required equipment, and materials are listed. Each lecture and each laboratory exercise is essentially self-contained to permit other schools to select material on the basis of available time and equipment and the objectives of their instructional program. In presenting the subject matter in as uncomplicated a form as possible, some concepts may have suffered from oversimplification, but the instructor can easily increase the degree of sophistication to the limit of student understanding. It is our belief that full appreciation and understanding of the subjects presented requires laboratory experience. Nonetheless, we are sure that the lecture material alone could be presented as review material or as indoctrination material to a group where x rays might be of peripheral interest. Selected sections from the course manuals have been used as source material for a one-quarter course in Continuing Education and for 2-day working topical seminars.

One of the most frustrating aspects of preparing teaching material is the ever-changing situation in regard to references. New books and technical papers make any list of references obsolete before it appears in print. The instructor must add references as they become available. The references cited must always reflect the experience, interests, and objectives of the instructor, the institution, and the students.

Equipment has been identified by model and manufacturer; instructors may substitute equivalent equipment or alter course content to make use of available equipment. This method of identification does not constitute a recommendation of particular equipment by either Oregon State University or the Bureau of Radiological Health, United States Department of Health, Education, and Welfare.

E. Dale Trout

E. Dale Trout, D.Sc., Project Director

Director
X-Ray Science and Engineering Laboratory
Oregon State University

GS-462 X-RAY MEASUREMENTS

SECTION I

LECTURES

LECTURE NO. 1

TITLE:	Interaction of X Rays with Matter
PURPOSE:	To study the fundamental interactions of x rays with matter
TIME:	One hour
VISUAL AIDS:	Blackboard Slide projector for slides illustrating basic photon interactions
HANDOUTS:	None
REFERENCES:	Attix, Roesch and Tochilin Radiation Dosimetry Johns and Cunningham The Physics of Radiology Radiological Health Handbook Ter-Pogossian Physical Aspects of Diagnostic Radiology

INTERACTION OF X RAY: WITH MATTER

I. Introduction

A knowledge of the basic interactions of x rays with matter is essential to the understanding of the principles of x-ray detection and measurement.

II. Definitions of Interactions

A. When x rays interact with matter they may lose energy and/or change their direction of travel.

1. Loss of energy is referred to as absorption.
2. Change in direction of travel is called scattering.
   a. Elastic scattering - no loss in energy
   b. Inelastic scattering - loss in energy

B. Ionization

1. Ions are free electrons or atoms carrying an electric charge.
2. Ionization is the process by which ions are formed.
   a. Generally result of removal of electron(s)
   b. Ion pair - positive and negative ion
      1) Negative ion - electron
      2) Positive ion - remaining atom

III. Mechanisms of Interactions

A. Photoelectric effect

1. An x-ray photon imparts all of its energy to a bound inner orbital electron of an atom. All or nothing energy transfer.
2. An electron is ejected and an ion pair is formed
   a. $(KE)_{e^-} = h\nu - w$
   b. $h\nu$ = initial photon energy
   c. w = atomic binding energy
3. The electron is called a photoelectron
   a. It has sufficient energy, in general, to produce many hundreds of additional ion pairs as it travels through matter expending its energy.

4. Let τ = fraction of x-ray photons removed from beam by photoelectric effect per unit thickness of absorbing material (Fig. 462-1).

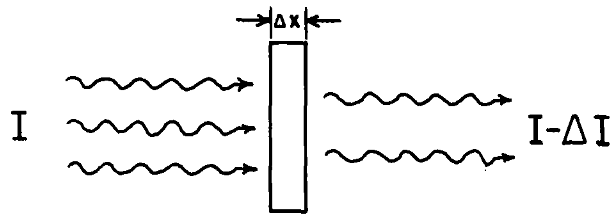


Figure 462-1 Photon Attenuation

a. I = number of incident photons, ΔI = number of photons removed by photoelectric effect in absorber of thickness ΔX

b. $\tau = -\frac{\Delta I}{I} / \Delta X \propto \frac{Z^4}{E^3}$

5. Photoelectric effect predominates at low energies and high Z materials.

a. For tissue the photoelectric effect becomes negligible above about 200 keV.

B. Compton effect

1. If a photon is incident upon a "free" or loosely bound electron it may impart part of its energy to the electron and be scattered.
2. The electron receiving energy is called a Compton electron.
3. The results of ionization are identical to those of the photoelectric effect.
4. The remaining photon energy appears as a lower energy photon traveling in a direction with an angle θ to the initial photon's direction of travel.

5. The energy of the scattered photon is a function of the initial photon energy and the angle of scatter (Fig 462-2)

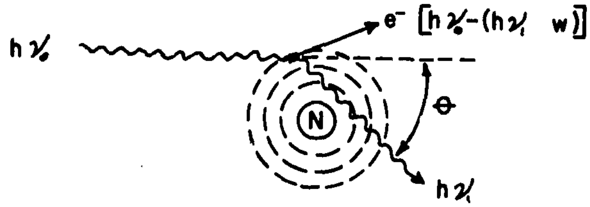


Figure 462-2 Compton scattering

$$h\nu_1 = \frac{h\nu_o}{1 + \frac{h\nu_o}{m_o c^2}(1 - \cos\theta)}$$

6. Let σ = fraction of x-ray photons removed from the beam by the Compton effect per unit thickness of absorber

   a. $\sigma \propto \frac{Z}{E}$

   b. The Compton effect predominates at intermediate energies, i.e. 600 keV-2.5 MeV.

C. Pair production

1. An x-ray photon interacts with the electric field of the nucleus giving up all its energy to the creation of a pair of "electrons".

   a. One electron is negatively charged (e^-)

   b. One positron is positively charged (e^+)

2. The energy threshold for pair production is 1.02 MeV Photon energy in excess of 1.02 MeV is shared as the kenetic energy of the "electron" pair.

3. Both the electron and positron interact with matter to produce ion pairs.

   This is the same process as Compton or photoelectric electrons.

4. The positron combines with an electron in annihilation producing two back to back 0.51 MeV photons (Fig. 462-3)

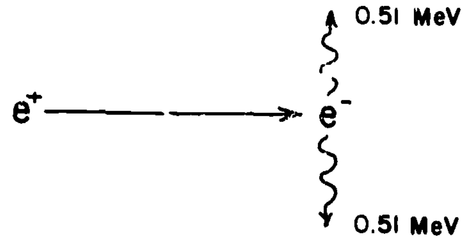


Figure 462-3 Annihilation process

5. Let k = fraction of x-ray photons removed from the beam by pair production per unit thickness of absorber.

   a. $k \propto Z^2 \ \ln E$ where $E > 1.02$ MeV

   b. Pair production predominates at high E and high Z

D. Linear attenuation coefficient (Fig. 462-4)

1. $\mu = \tau + \sigma + k = \dfrac{-\Delta I}{I} / \Delta X$

2. $I = I_o e^{-\mu x}$ or $\dfrac{I}{I_o} = e^{-\mu x}$

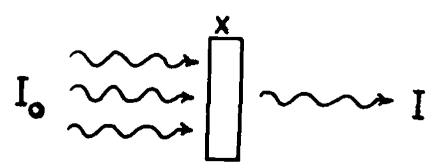


Figure 462-4 Linear attenuation coefficient

3. Unit, cm^{-1}

IV. <u>Diagrams of Interactions</u>

A. Photoelectric effect (Fig. 462-5)

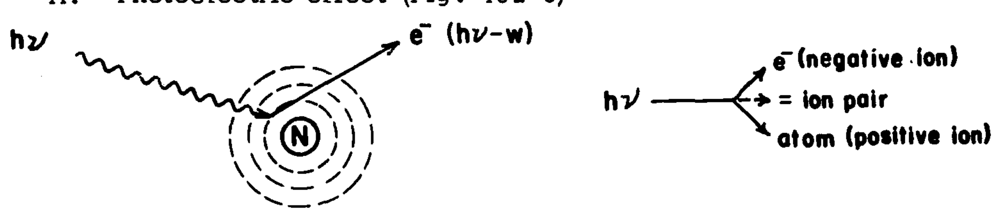


Figure 462-5 Photoelectric effect

B. Compton effect (Fig. 462-6)

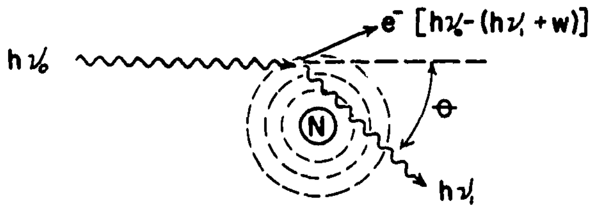


Figure 462-6. Compton effect

C. Pair production (Fig. 462-7)

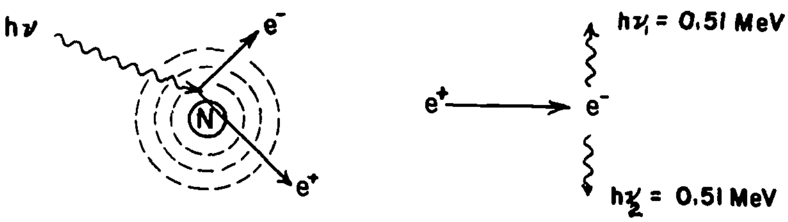


Figure 462-7. Pair production

LECTURE NO. 2

TITLE:	Attenuation of X Rays
PURPOSE:	To study the attenuation and absorption of x rays by matter
TIME:	Two hours
VISUAL AIDS:	Blackboard
HANDOUTS:	None
REFERENCES:	Attix, Roesch and Tochilin <u>Radiation Dosimetry</u>
	ICRU Report 11
	Johns and Cunningham <u>The Physics of Radiology</u>
	Whyte <u>Principles of Radiation Dosimetry</u>

ATTENUATION of X RAYS

I. Introduction

The three principle kinds of x- and γ-ray interactions with matter are the photoelectric effect, Compton effect and pair production. In these interactions the photon tends to lose much or all of its energy in a single interaction. In our study we are concerned with the combined effect of all interactions. (Interactions refer to processes whereby the energy or direction of the x-ray photon is altered). The beam attenuating effect of these interactions may be described by various attenuation coefficients.

II. Absorption and Attenuation Coefficients

A. Linear attenuation coefficient - μ

1. Defined as the fractional change in intensity per unit thickness due to interactions in a given material.

   a. $\mu = \Delta N / N \Delta X$

   b. ΔN = number of photons actually removed from beam in thickness ΔX.

2. It is a function of density and atomic number.

B. Mass attenuation coefficient - μ / ρ

1. Defined as the fractional decrease in intensity per unit mass due to interactions in a given material

   a. $\mu / \rho = \Delta N / N \Delta X \rho = \mu_m$

   b. ρ = density of the material

2. For x or γ radiation

$$\mu/\rho = \tau / \rho + \frac{\sigma}{\rho} + \frac{\sigma \, coh}{\rho} + \frac{k}{\rho} = \mu_m \, cm^2 / g$$

III. Behavior of μ / ρ or μ_m

A. In low Z materials i e. oxygen:

1. μ_m falls rapidly in the 10 - 100 keV region
2. μ_m slowly decreases in the 100 keV - 2 MeV region. Compton is the predominate interaction.
3. μ_m increases in the region above 50 MeV

B. In medium Z materials i.e. copper:

1. μ_m falls until both the photoelectric and Compton effects are equal, which occurs at about 125 keV.
2. μ_m slowly decreases until both Compton and pair production effects are equal, which occurs at about 9 MeV. Compton predominates in the 500 keV - 3 MeV region.
3. μ_m increases in the region above 8 MeV.

C. In high Z materials i.e. lead:

1. μ_m follows the same trend but there is no region where the Compton effect alone is important.
2. The photoelectric effect = Compton effect at about 500 keV
3. The total effect is about 75% Compton at 1 - 2 MeV
4. The minimum μ_m occurs at about 3 MeV
5. The Compton effect = pair production at about 4.5 MeV

IV. Attenuation of X Rays

A. Assume narrow beam geometry and a monoenergetic beam of x rays (Fig. 462-8)

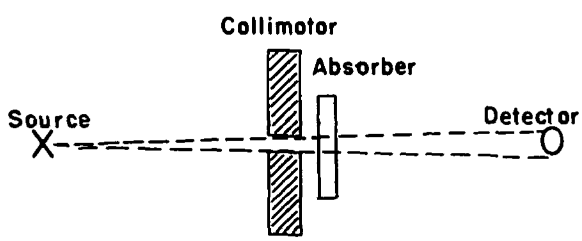


Figure 462-8 Narrow beam geometry

B. It can be shown that $I = I_o e^{-\mu x}$ where:

1. I_o = initial beam intensity at the detector
2. I = beam intensity at the detector after passing through a thickness of absorber
3. x = thickness of absorber
4. μ = linear attenuation coefficient of the material for indirectly ionizing particles

C. Half-value layer

1. Defined as the thickness of a specified absorber (material) required to reduce the x-ray beam intensity by a factor of 1/2. (Fig. 462-9)

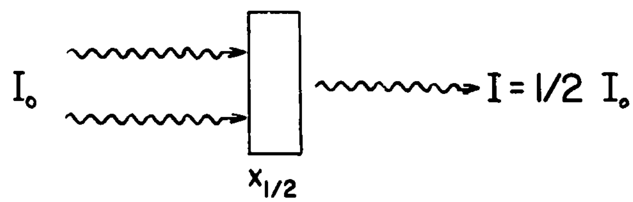


Figure 462-9 Half-value layer

2. For a monoenergetic x-ray beam:
   a. $I = I_o e^{-\mu x}$
   b. $\frac{I}{I_o} = 1/2 = e^{-\mu x_{1/2}}$
   c. $\therefore e^{\mu x_{1/2}} = 2$ and $\mu x_{1/2} = \ln 2 = 0.693$
   d. $HVL = x_{1/2} = \frac{0.693}{\mu}$

3. Example: calculate the HVL in Al for 0.1 MeV (100 keV) photons
   a. $\mu/\rho = 0.167\ cm^2/g$
   b. $\rho\ (Al) = 2.7\ g/cm^3$
   c. $\mu = (\mu/\rho)\ \rho = (0.167)\ (2.7) = 0.45\ cm^{-1}$
   d. $HVL = 0.693/0.45 = 1.54$ cm Al = 15.4 mm Al

D. Build-up factor

1. Defined to account for the scatter contribution under broad beam conditions (Fig. 462-10)

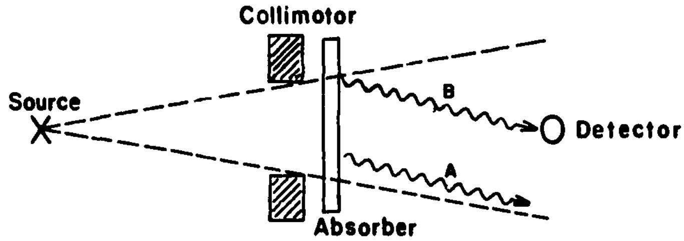


Figure 462-10 Broad beam geometry

2. Build-up factor $B = \frac{\text{observed broad beam intensity}}{\text{narrow beam intensity}}$

3. $B = \frac{I}{I_o \exp\ (\mu/\rho)\rho x}$

4. $\therefore I = I_o B e^{-(\mu/\rho)\ \rho x}$

5. B depends upon:

   a. Geometry

   b. Absorber material

   c. Absorber thickness

   d. Primary photon energy

E. Backscatter

1. When a photon beam strikes the surface of an absorber, the intensity in front of the absorber is greater than that without the absorber. (Fig. 462-11)

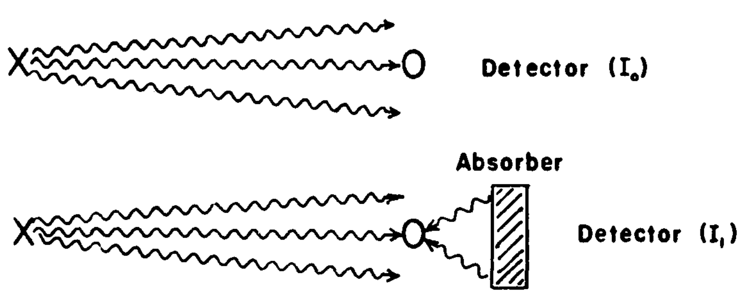


Figure 462-11 Backscatter

2. Intensity $I_1 > I_o$ due to scattering of radiation from the absorber back to the detector.
3. Backscatter depends upon the:
   a. Incident photon beam energy
   b. Beam area (size)
   c. Atomic number of absorber
4. Backscatter varies from a negligible value to more than 50% of the incident exposure under certain conditions.

GS-462

PROBLEM SET NO. 1

1. Calculate the fractional decrease in beam intensity when a beam of 50 keV x rays passes through a 1.00 cm aluminum absorber.

2. Compute the HVL for 100 keV x rays in aluminum and copper.

3. The exposure rate of 50 keV x rays incident upon an aluminum absorber is 1 R/hr. If the transmitted exposure rate is 1 mR/hr, what is the thickness of the absorber?

4. Find the photon energy of a beam of monoenergetic x rays if the HVL is 0.61 cm lead.

GS-462

PROBLEM SET NO. 1

KEY

1. Calculate the fractional decrease in beam intensity when a beam of 50 keV x rays passes through a 1.00 cm aluminum absorber.

Ans. For 50 keV photons, μ/ρ (Al) = 0.36 cm^2/g

and ρ = 2.7 g/cm^3

$I = I_o e^{-\mu x}$ so $\frac{I}{I_o} = e^{-\mu x} = e^{-(0.36)(2.7)(1.00)}$

$= e^{-0.973} = 0.375$

Fractional decrease: 1 - 0.375 = 0.625

2. Compute the HVL for 100 keV x rays in aluminum and copper.

Ans. $HVL = \frac{0.693}{\mu} = \frac{0.693}{(\mu/\rho)(\rho)}$

For Al at 100 keV μ/ρ = 0.17 cm^2/g and ρ = 2.7 g/cm^3

For Cu at 100 keV μ/ρ = 0.47 cm^2/g and ρ = 8.96 g/cm^3

$HVL_{Al} = \frac{0.693}{(0.17)(2.7)} = 1.51$ cm

$HVL_{Cu} = \frac{0.693}{(0.47)(8.96)} = 0.164$ cm

3. The exposure rate of 50 keV x rays incident upon an aluminum absorber is 1 R/hr. If the transmitted exposure rate is 1 mR/hr, what is the thickness of the absorber?

Ans. $I = I_o e^{-\mu x}$. At 50 keV $\mu = (\mu/\rho)(\rho) = (0.36)(2.7) = 0.972$

$\frac{I}{I_o} = \frac{1.0}{1000} = e^{-\mu x} = 0.001$

$e^{-6.91} = 0.001$ so $x = \frac{6.91}{\mu} = \frac{6.91}{0.972} = 7.12$ cm

GS-462 Problem Set No. 1
KEY

4. Find the photon energy of a beam of monoenergetic x rays if the HVL is 0.61 cm lead.

Ans. $\mathrm{HVL} = \dfrac{0.693}{\mu} = \dfrac{0.693}{(\mu/\rho)(\rho)}$

For lead $\rho = 11.4\ \mathrm{g/cm^3}$

$$\mu/\rho = \frac{0.693}{(0.61)(11.4)} = \frac{0.693}{6.95} = 0.0997\ \mathrm{cm^2/g}$$

so keV for μ/ρ of 0.1 for lead $\approx$ 700 keV

LECTURE NO. 3

TITLE:	Radiation Quantities and Units
PURPOSE:	To present the quantities and units used in the study of x-ray measurements
TIME:	One hour
VISUAL AIDS:	Blackboard
HANDOUTS:	None
REFERENCES:	ICRU Report 11

RADIATION QUANTITIES AND UNITS

I. Introduction

In order to understand the techniques used in x-ray measurements one must be familiar with the terminology used. This requires that we define certain radiation quantities and units.

II. Special Units

A. Roentgen for exposure (R)

1. 1 R = 2.58 x 10^{-4} coulomb/kg air
2. 1 R = 1 esu/0.001293 g air
3. 1 R = 1 esu/cm^3 dry air at STP
4. With present techniques it is difficult to measure exposure for photon energies below a few keV and above a few MeV.

B. Rad for absorbed dose

1. 1 rad = 100 ergs/g material
2. 1 rad = 0.01 Joule/kg material
3. When rad may be confused with the symbol for radian, rd may be used as the symbol for rad.

III. Definitions of Radiation Quantities

A. Directly ionizing particles

1. Charged particles with sufficient kenetic energy to produce ionization by collision.
2. Examples: electrons, protons, α particles

B. Indirectly ionizing particles

1. Uncharged particles which can liberate directly ionizing particles or can initiate a nuclear transformation.
2. Examples: photons, neutrons

C. Ionizing radiation

1. Any radiation consisting of directly or indirectly ionizing particles or a mixture of both.

D. Energy imparted

1. Difference between the sum of the energies of all ionizing particles which have entered the volume and the sum of the energies of all those which have left the volume. Excludes the energy equivalent of any increase in rest mass that took place in nuclear or elementary particle reactions.

2. The term energy imparted to matter is identical to the quantity called integral absorbed dose.

3. Energy imparted cannot always be equated to heat produced because of possible changes in interatomic bond energies.

E. Exposure (X)

1. Special unit-roentgen

2. $X = \dfrac{\Delta Q}{\Delta m}$

ΔQ = sum of the electrical charges on all ions of one sign produced in air when all the electrons (negatrons and positrons) liberated by photons in a volume element of air whose mass is Δm are completely stopped in air.

F. Absorbed dose (D)

1. Special unit-rad

2. $D = \dfrac{\Delta E_D}{\Delta m}$

ΔE_D = energy imparted by ionizing radiation to the matter in a volume element and Δm is the mass of the matter in that volume element.

G. Other quantities of interest

1. Particle fluence $\Phi = \frac{\Delta N}{\Delta a}$
2. Flux density (particle fluence rate)
3. Energy fluence $\psi = \frac{\Delta E\psi}{\Delta a}$
4. Intensity (I), energy flux density, energy fluence rate $= \frac{\Delta \psi}{\Delta t}$
5. Kerma $K = \frac{\Delta E_k}{\Delta m}$
6. Mass attenuation coefficient $\mu / \rho = \tau / \rho \quad \frac{\sigma}{\rho} + \frac{\sigma\,coh}{\rho} + \frac{k}{\rho}$
7. Mass energy transfer coefficient $\mu_k / \rho = \frac{\tau\ a}{\rho} + \frac{\sigma\ a}{\rho} + \frac{K_a}{\rho}$
8. Mass stopping power $S/P = \frac{1}{\rho} \quad \frac{dE}{dl}$
9. Average energy (W) expended in gas per ion pair formed $W = \frac{E}{N_w}$

H. Relative biological effectiveness (RBE)

Factor used in radiobiology to compare biological effectiveness of absorbed doses of different types of ionizing radiations.

I. Dose equivalent (DE)

1. Used for radiation protection purposes
2. DE = (D) (QF) (DF) ----
   a. D = Absorbed dose in rads
   b. QF = quality factor, LET dependent factor, that expresses on common scale for ionizing radiations the irradiation incurred by exposed persons
   c. DF = distribution factor, expresses modification of biological effect due to nonuniform distribution of internally deposited isotopes.
   d. Other modifying factors may be introduced as needed.
3. Unit of dose equivalent-rem
   a. Equal to dose in rads times appropriate modifying factors.
   b. For our purposes we can assume 1 R = 1 rad = 1 rem.

LECTURE NO. 4

TITLE:	X-Ray Detection
PURPOSE:	To outline the basic principles of x-ray detection
TIME:	One hour
VISUAL AIDS:	Blackboard
HANDOUTS:	None
REFERENCES:	Attix, Roesch and Tochilin Radiation Dosimetry
	Johns and Cunningham The Physics of Radiology
	Spiers and Reed Radiation Dosimetry
	Ter-Pogossian Physical Aspects of Diagnostic Radiology

X-RAY DETECTION

I. Introduction

X-ray detection systems depend, for their operation, on ionization and/or excitation produced in the system by x-ray interactions with the system (matter).

II. Media

A. Gases

1. Usually air enclosed in a chamber having electrically conducting walls and a collecting (center) electrode. (Fig. 462-12)

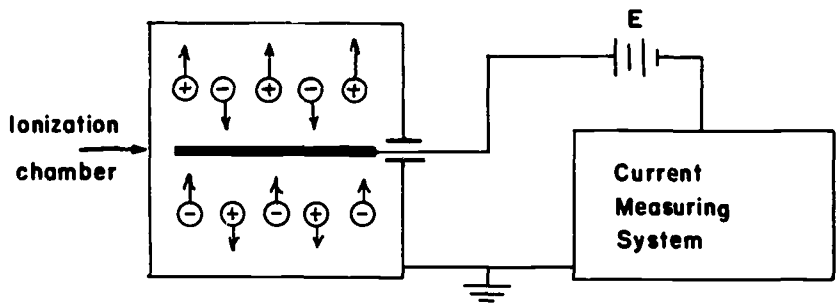


Figure 462-12 Gas ionization system

2. Ions produced as a result of interactions of the x rays with the gas (air) are collected by the electrostatic field (E) between chamber walls and collecting (center) electrode.

3. Ionization current $\propto$ incident x-ray intensity.

B. Photographic emulsions

1. Film emulsion

Silver bromide (AgBr) suspended in gelatin.

2. Ionization within emulsion renders AgBr crystals susceptable to action of developer.

a. Developer reduces Ag^+ to Ag producing darkening of the film.

b. The degree of darkening (density) is measured with a "densitometer".

c. Film density $\propto$ quantity of incident x rays.

C. Luminescent detectors

1. Scintillation crystals

a. Excitation of crystals through x-ray interactions.

b. Results in "immediate" de-excitation with the wavelength of energy emitted in the visible light region.

c. Sodium iodide is used extensively

d. A photomultiplier tube, photocell, etc. is used to detect the emitted light.

e. The quantity of light $\propto$ energy of the incident x rays

f. Fluorescence

(1.) Fluorescent screens - Zn CdS

(2.) Intensifying screens $Ca\ WO_4$

2. Thermoluminescent crystals

a. Excitation is produced through x-ray interactions.

b. The excitation energy is stored by the crystal.

c. De-excitation is induced by crystal heating.

d. De-excitation energy is emitted as light and detected by a photomultiplier tube.

e. The light emitted $\propto$ quantity of incident x rays.

f. Commonly used crystals:

(1.) LiF

(2.) CaF_2

(3.) $CaSO_4$

3. Radiophotoluminescent glass

a. The crystal is excited through x-ray interactions.

b. Materials fluoresce when exposed to ultra violet light.

c. Fluorescence is measured with a fluorimeter.

d. The light intensity $\propto$ quantity of x-ray interactions.

e. One material used is silver activated metaphosphate glass.

D. Chemical solutions

1. Ionization from x-ray interactions induces a chemical reaction.

2. The end products produced $\propto$ quantity of incident x rays.

3. Fricke dosimeter

a. Ferrous sulfate is converted to ferric ions when exposed to x rays.

b. $Fe^{++} + h\nu \rightarrow Fe^{+++}$ in dilute sulfuric acid solution.

c. Quantity of Fe^{+++} (ferric ions) produced $\propto$ to the energy absorbed.

(1.) Determined by absorption spectroscopy or chemical titration.

(2.) Not a sensitive system.

LECTURE NO. 5

TITLE:	Gas Ionization Instrumentation
PURPOSE:	To study the characteristics of gas ionization instruments
TIME:	Two hours
VISUAL AIDS:	Blackboard Condenser R-meter, GM survey meter, DC amplifier survey meter, vibrating reed survey meter
HANDOUTS:	None
REFERENCES:	Attix, Roesch and Tochilin Radiation Dosimetry Johns and Cunningham The Physics of Radiology Spiers and Reed Radiation Dosimetry Ter-Pogossian Physical Aspects of Diagnostic Radiology

GAS IONIZATION INSTRUMENTATION

I. Introduction

A. Basic x-ray measuring instruments are designed to measure the number of ions formed in a gas through interaction of x rays.

B. The number of ions collected in a gas ionization chamber is a function of the electric field strength between the collecting electrodes.

C. Diagram of basic system (Fig. 462-13)

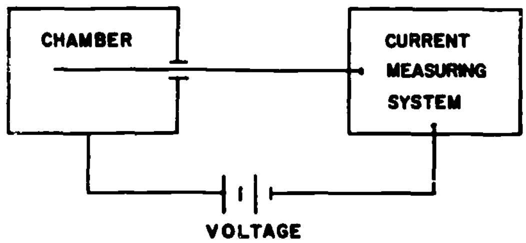


Figure 462-13 Diagram of basic system

II. Charge Collection

There are at least 5 separate response regions, for a given ion chamber, which are dependent upon chamber voltage. (Fig. 462-14)

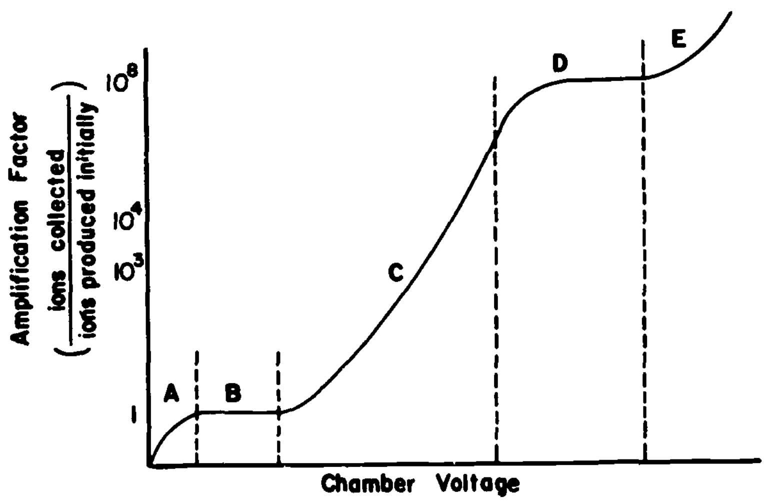


Figure 462-14 Gas amplification vs chamber voltage

A. Recombination region

1. Low chamber voltage with resulting weak electric field
2. Some ions recombine before they are collected.
3. Recombination decreases as the chamber voltage increases.

B. Ionization chamber region

1. The voltage is high enough so that there is effectively no recombination.
   a. All of the ions produced are collected.
   b. The gas amplification is one.
2. This region is best suited for the measurement of exposure.
3. The region persists over a fairly large voltage range.

C. Proportional chamber region

1. As the voltage is increased above the ionization chamber region, the electric field accelerates the electrons formed to a velocity high enough to produce additional ionization (gas amplification--by collision).
2. For every initial ion pair formed by the radiation, a larger number is received by electrodes.
3. The number of ions collected is proportional to the number of ions initially formed.
4. Typical amplification is $10^3 - 10^4$
5. This requires a very stable voltage supply since the amplification factor changes rapidly with voltage.
6. You no longer measure current flow but detect individual ionizing events.
7. This region is not basically suited for measuring exposure.
8. This region is used extensively for charged particle measurements.

Particle	Primary Ions	Ions Collected
α	10^5	10^8
β	10^3	10^6

9. You can differentiate between α and β by the pulse size.

D. Geiger-Mueller region

1. Above the proportional region the amplification factor may reach 10^8.
2. Even a low energy β or x ray can initiate sufficient ion formation to cause complete discharge of the chamber
3. You count individual events
4. This region is not suited for the measurement of exposure

E. Continuous discharge region

1. Voltages above GM result in continuous discharge (arcing)

III. Ion Recombination

A. In the ionization chamber region some ion recombination can and does occur. The two basic processes of recombination are:

1. Initial recombination
   a. These are ions that recombine in close proximity to their point of formation.
   b. Some initial recombination will occur regardless of chamber voltage.
2. General recombination
   a. This is random recombination which occurs at other than points of ion formation
   b. General recombination can be calculated. It is a function of:
      1.) Chamber shape (spherical, cylindrical, parallel plate)
      2.) Electrode spacing
      3.) Gas (usually air)
      4.) Chamber voltage
      5.) Exposure rate
      6.) Chamber construction

3. The ratio of ions collected to ions formed is termed collection efficiency F.
   a. You strive for 0.99+ efficiency
   b. This determines intensity limit for ion charge collecting systems.

IV. <u>Exposure Rate Ionization Chamber Instruments</u>

A. DC amplifier type (Fig. 462-15)

1. This includes direct coupled systems such as the Victoreen model 510 Roentgen Ratemeter, model 740 "Cutie Pie" survey meter, and model 592 survey meter.

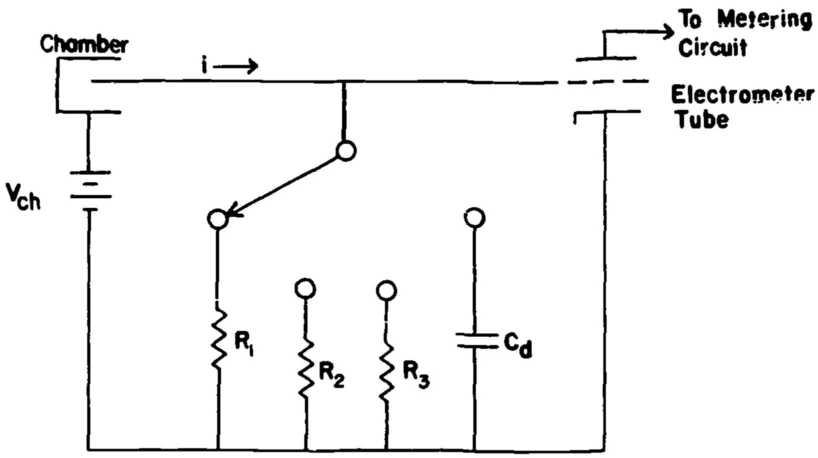


Figure 462-15 DC amplifier

2. The electrometer tube is usually a triode, small in size, with very high grid leakage resistance.
3. The major problem in DC amplifiers is drift. A change in system voltages will produce a signal which is indistinguishable from the ion current.
4. Example: Victoreen 740
   a. Chamber volume = 586 cm^3, full-scale on X 1 range, 25 mR/h
   b. R1 = 4 x 10^{11} ohms, scale range X 1

c. $R2 = 4 \times 10^{10}$ ohms, scale range X 10

d. $R3 = 4 \times 10^{9}$ ohms, scale range X 100

e. Let exposure rate $\frac{dx}{dt}$ = 25 mR/h and use X 1 range,

$R = 4 \times 10^{11}$ ohms, $i = \frac{dQ}{dt}$ = coulombs/sec

f. 1 Roentgen = 1 esu/cm^3, 1 coulomb = 3×10^9 esu

$$i = v \frac{dx}{dt} = (586\ cm^3)\ (25 \times 10^{-3}\ R/h)\ (1\ esu/cm^3/R)$$

$$(1\ h/3.6 \times 10^3\ sec)\ (1\ coulomb/3 \times 10^9\ esu)$$

$$= 0.136 \times 10^{-11}\ amp.$$

g. The voltage drop across resistor R 1 (grid voltage on electrometer tube) is:

$v = iR = (0.136 \times 10^{-11})\ (4 \times 10^{11}) = 0.544$ volts

h. Assume the above except let dx/dt = 2500 mR/h and

$R3 = 4 \times 10^9$ ohms (X 100 range)

$i = 0.139 \times 10^{-9}$ amp

$v = (0.139 \times 10^{-9})\ (4 \times 10^9) = 0.544$ volts

B. AC amplifier types - Fig. 462-16

1. A vibrating reed or vibrating capacitor converts the d.c. signal to a.c. (Victoreen model 440 and 444 survey meters, Victoreen model 555 Radocon)

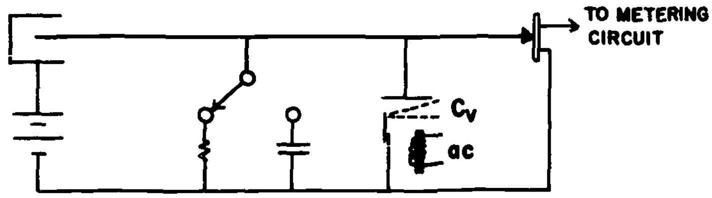


Figure 462-16 Vibrating reed electrometer

2. The amplified signal is drift-free

3. An a.c. amplifier permits greater sensitivity.

V. <u>Exposure (charge collecting/dissipating) Systems</u>

A. Condenser chamber type (R-meter) (Fig. 462-17)

1. A capacitor is charged and then partially discharged due to the ion current flow

a. Charge $\propto$ voltage $\propto$ exposure

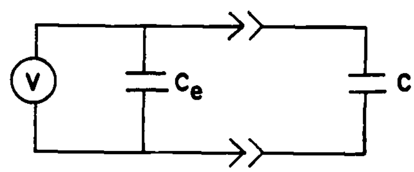


Figure 462-17 R-meter equivalent circuit

1.) V= electrometer charger-reader

2) C_e= electrometer capacitance

3.) C = ion chamber capacitance

b. Charge $Q = CV$ so $\Delta Q = C \Delta V \propto R$

1.) $Q = vR$ esu $= \frac{vR}{3 \times 10^9}$ coulombs

2.) $\frac{\Delta V}{R} \propto \frac{\Delta V}{\Delta Q} \propto \frac{1}{C}$

3.) $\Delta V = \frac{vR}{3 \times 10^9} \cdot \frac{1}{C}$

$\frac{\Delta V}{R}$ = sensitivity = S

2. In use, C and C_e charged to V_o

a. When the chamber is exposed to x rays, V_o on C drops to V_1. When C is reconnected to C_e (still charged to V_o) the charge on the two capacitors is shared and the electrometer indicates a "shared" voltage, V_s.

1.) $V_s < V_o$

2.) $V_s > V_1$

b. The measured voltage drop = $V_o - V_s = V_m$

c. The true voltage drop on chamber = $V_o - V_1 = V_t$

d. If Q = charge liberated by the exposure, then:

1.) $V_t = \frac{Q}{C}$

2.) $V_m = \frac{Q}{C + C_e}$

3.) $\frac{Vt}{V_m} = \frac{C + C_e}{C}$

3. In the R-meter, $V_o \approx$ 525 volts and V_m (the full-scale voltage) $\approx$ 275 volts.

a. A 25 chamber would have sensitivity, S, of

$$\frac{525 - 275V}{25R} = 10\ V/R$$

b. The chamber capacitance, C, is typically about 50 pF

c. Knowing V_o, S of the system and C, we can calculate C_e, S of chamber and the effective volume, v, of the chamber.

Example:

1.) Assume the 25 R chamber with V_o = 525 volts and S for the electrometer/chamber system = 10 V/R. When the fully-charged chamber is connected to the completely discharged electrometer, the scale reading is 10.0 R (discharge check).

2.) A scale reading of 10.0 R corresponds to a voltage drop of (10 V/R) (10 R) = 100 volts and a final voltage of 525 - 100 = 425 volts. This loss of charge from the chamber Q = CV = (50 pF) (100 V) charged the electrometer to 425 volts so

$$C_e = C\frac{V_{drop}}{V_{read}} = (50)\left(\frac{100}{425}\right) \therefore C_e = 11.8\ pF$$

3.) $\frac{V_t}{V_m} = \frac{C + C_e}{C} = \frac{50 + 11.8}{50} = 1.24$ so

$V_t = 1.24\ V_m = (1.24)\ (100) = 124$ volts,

$\therefore$ S of chamber = 12.4 V/R

4.) $V = \frac{vR}{3 \times 10^9\ C}$, $v = \frac{V\ (3 \times 10^9\ C)}{R}$ and $\frac{V}{R} = S$

$v = (12.4)\ (3 \times 10^9)\ (50 \times 10^{-12}) = 1.86\ cm^3$

B. Vacuum tube electrometers (Baldwin-Farmer)

1. Use separate charging and reading systems (Fig. 462-18).

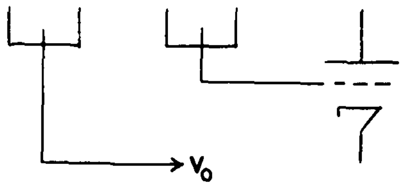


Figure 462-18 Vacuum tube electrometer

2. Let V_o = charging voltage

X_o = voltage read after charging

$X_o < V_o$ due to charge sharing

$$\frac{V_o}{X_o} = \frac{C + C_e}{C}$$

If the chamber is recharged and exposed and we call the resulting reading X_1, then the voltage loss is $X_o - X_1 = V_m$ and $V_t = (X_o - X_1)$

$$\left(\frac{C + C_e}{C}\right) = (X_o - X_1)\ \frac{V_o}{X_o} \quad \text{and } S = \frac{V_t}{R}$$

VI. <u>Classes of Instruments</u>

A. Survey Instruments ($\pm$ 10 - 20 %)

B. Laboratory Instruments ($\pm$ 1 - 5 %)

C. Personnel Monitoring Instruments ($\pm$ 5 - 20 %)

LECTURE NO. 6

TITLE: Energy Dependence of Ionization Chamber Instruments

PURPOSE: To discuss the factors which affect the energy dependence of x-ray measuring instruments

TIME: One hour

VISUAL AIDS: Blackboard
Standard Air Chamber

HANDOUTS: None

REFERENCES: Attix, Roesch and Tochilin
<u>Radiation Dosimetry</u>

Snell
<u>Nuclear Instruments and their Uses</u>

Spiers and Reed
<u>Radiation Dosimetry</u>

ENERGY DEPENDENCE OF IONIZATION CHAMBER INSTRUMENTS

I. Energy Dependence

A. Instrument response per roentgen as a function of photon energy. Response is the ratio of the indicated to true exposure. (Fig. 462-19)

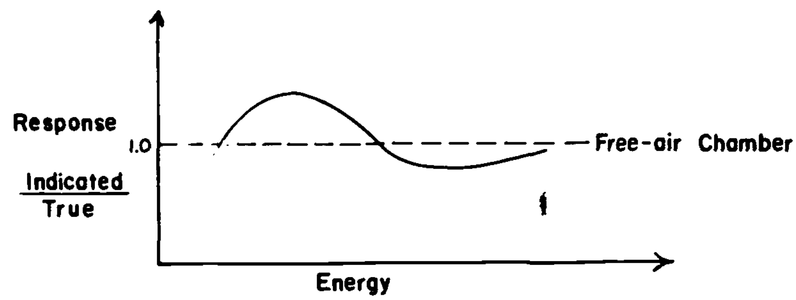


Figure 462-19 Response vs Energy

II. Free Air (Standard Air) Chamber

A. The primary standard used to measure ionization in air due to x- or γ- radiation is the standard air chamber. (Fig. 462-20)

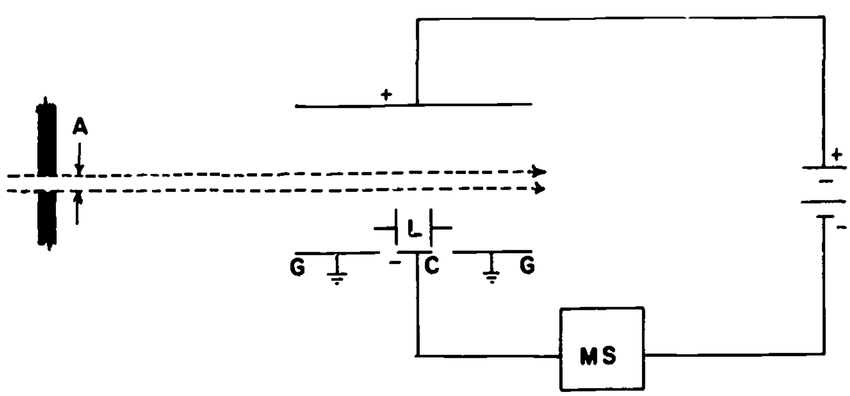


Figure 462-20 Standard Air Chamber

B. The x rays interact in air and all ions are collected in air.

C. An accurately defined air volume, A x L, is defined.

D. All ions produced outside the defined volume by primary electrons originating within the defined volume must be collected.

1. Therefore, as photon energy increases, the distance between the defined air volume and the collecting plates must increase so that secondary electrons do not strike the plates and lose ionization potential.

2. The upper limit is about 2 - 3 MeV

   a. The maximum range of a 3 MeV electron in air at STP is about 45 feet.

   b. High energy chambers are operated at high air pressure.

E. Electronic equilibrium must exist in the collecting volume.

III. Electronic Equilibrium

A. If the number of electrons entering a volume element is equal to the number leaving the element, then electronic equilibrium exists.

B. This condition will exist at a depth within a medium which is at least equal to that of the maximum range of the electrons.

C. Consider a medium in which the exposure in a volume element is desired (Fig. 462-21).

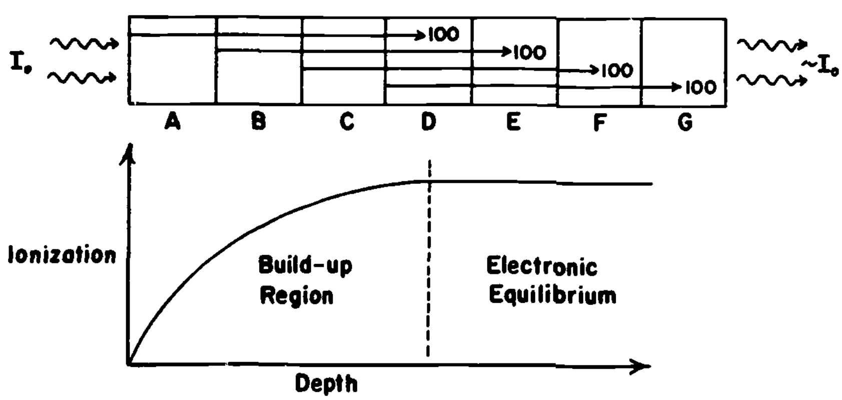


Figure 462-21 Electronic Equilibrium

1. Assuming negligible attenuation, the exposure in each square would be the same.
2. Assume that there is only one interaction in each volume element.
3. We need to collect all the secondary electrons produced by primary electron originating in that volume.
4. Assume that the primary electron range is R and that 100 secondary electrons (ion pairs) are formed along its path.
5. Square D is traversed by 4 primary electron tracks. When each segment is added together the total track length through D is R, therefore, 100 ion pairs were produced in D (the same number that originated from volume A).

IV. <u>Ion Chamber Instruments</u>

A. The standard air chamber lacks mobility. This has lead to the development of "secondary standard" instruments and other instruments such as the condenser R-meter.

1. Consider mass of air where electronic equilibrium exists within the small volume element D (Fig. 462-22).

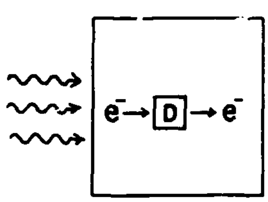


Figure 462-22 Block of Air with Volume Element D

2. If we "condense" the air around D and form the wall of a chamber with it, electronic equilibrium will still exist. (Fig. 462-23)

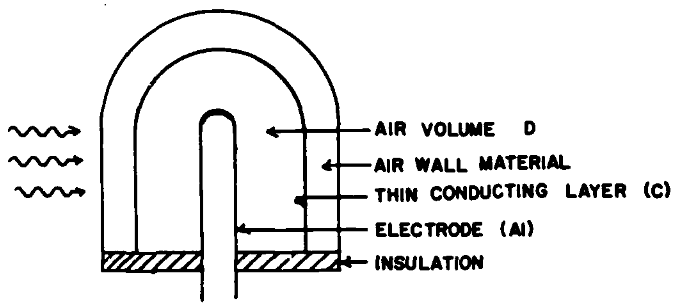


Figure 462-23 Air Wall Ionization Chamber

3. Need "air equivalent" wall.

   a. $Z_{air} = 7.64$

   b. Walls are usually bakelite (C_6H_5OH), polystyrene or nylon coated with graphite (carbon) with a center electrode of aluminum. By adjusting the electrode size and the amount of carbon, it is possible to make the chamber appear to be "air equivalent".

B. Factors contributing to poor energy response

1. Improper wall thickness

   a. If the wall thickness is much too great (more than the equilibrium thickness), attenuation will occur in wall and the response will decrease.

   b. If the wall thickness is less than the equilibrium thickness, more electrons will leave the volume than will enter and the response will decrease.

2. Non air-equivalent wall

   a. The greater the difference in μ/ρ between the wall material and air, the greater will be the energy dependence of the chamber.

b. Bakelite or plastic chamber walls are the least energy dependent since their atomic number approximates air.

c. Metal is not used as a wall material, especially at low photon energies, due to the photoelectric effect.

V. X-Ray Detectors Involved

A. Ionization chambers

B. Photographic emulsions

C. Luminescent media

D. Chemical media

LECTURE NO. 7

TITLE: Survey Meter Time Response

PURPOSE: To study the factors influencing the time response of x-ray survey instruments

TIME: One hour

VISUAL AIDS: Blackboard

HANDOUTS: None

REFERENCES: Attix, Roesch and Tochilin
Radiation Dosimetry

SURVEY METER TIME RESPONSE

I. Introduction

In diagnostic radiographic equipment and techniques, the exposures are often short (high current, short time) and the equipment itself does not readily provide tube currents low enough to permit long (several seconds) exposure times without overloading the x-ray tube. In evaluating personnel exposure in diagnostic procedures, the x-ray equipment must be operated under "worst possible conditions" as far as kVp and beam direction are concerned. The end result of this is that a survey instrument, used to measure the instantaneous exposure rate, may not "have time" to reach an equilibrium reading during the time x ray is on. The fact that it takes time for a survey meter to reach a steady-state reading is of importance when exposure times are less than the instrument response time.

II. Factors Influencing Time Response

A. The inertia of the readout meter movement

1. Most survey meters use a d.c. microammeter as the readout element.

2. Meter inertia is usually negligible compared to other sources of reading delay.

B. The RC time constant of the circuit

1. Time constant in seconds is R (resistance in ohms) times C (capacitance in farads)

a. It is the time required for meter to indicate (1 - 1/e) or 63% of its final steady-state reading.

2. In ion chamber instruments: (Fig. 462-24)

   a. C = chamber capacitance (C_h) and distributed capacitance (C_d) of associated circuitry.

   b. R = load resistor (in most cases).

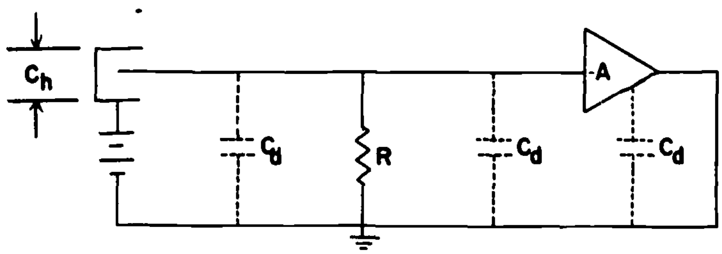


Figure 462-24 Survey Meter Electrical Diagram

   c. Sensitivity is changed by switching in more or less load resistance

   d. As a result, the time constant may be different from one range to another. R is high, often 10^8 - 10^{12} ohms, so it is important that C be low.

3. In GM survey meter instruments:

   a. R and C are in the output meter circuit

      1) The meter shunt resistance is changed to change range.

      2) As a result, time constant is uniform regardless of range.

      3) Time constant is intentionally varied by changing the capacitance in this circuit.

LECTURE NO. 8

TITLE:	X-Ray Beam Factors
PURPOSE:	To discuss x-ray field distribution, value layers and the homogeneity coefficient
TIME:	Two hours
VISUAL AIDS:	Blackboard Slide projector and slides from papers by Trout, et al (see references below)
HANDOUTS:	Reprints of references by Trout, et al.
REFERENCES:	Atlee and Trout A Study of Roentgen-Ray Distribution at 60-140 kVp
	ICRU Report 10d
	Trout, Kelley and Lucas Determination of Half-Value Layer
	Trout, Kelley and Lucas The Second Half-Value Layer and the Homogeneity Coefficient

X-RAY BEAM FACTORS

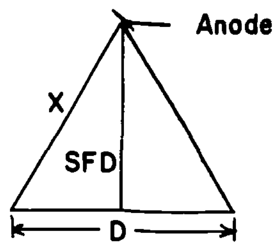
I. <u>Introduction</u>

The distribution of radiation across the x-ray field is not uniform due to the inverse-square law, attenuation within the target and attenuation in the plane filtration external to the x-ray tube unit.

II. <u>Inverse-square Law Effect</u>

A. The distance from the focal spot of the x-ray tube to various points on the useful plane field will be different.

B. The magnitude of the inverse-square law effect can be calculated if the geometry is known. (Fig. 462-25)



SFD = source-film distance

D = field diameter

x = distance from source to edge of field

Figure 462-25 Inverse-square Law Effect

1. Example: Calculate the magnitude of the I.S.L. effect if SFD = 50 cm, D = 20 cm, field center exposure 100%

a. $x^2 = (SFD)^2 + (\frac{D}{2})^2$

$= (50)^2 + (10)^2$

$= 2600$

$x = 51$ cm

b. $M = 100 \frac{(50)^2}{(51)^2}$

$= 96\%$

c. Thus there is a 4% reduction due to I.S.L.

III. Attenuation within Target

A. Field distribution parallel to tube axis for typical diagnostic x-ray tube. (Fig. 462-26)

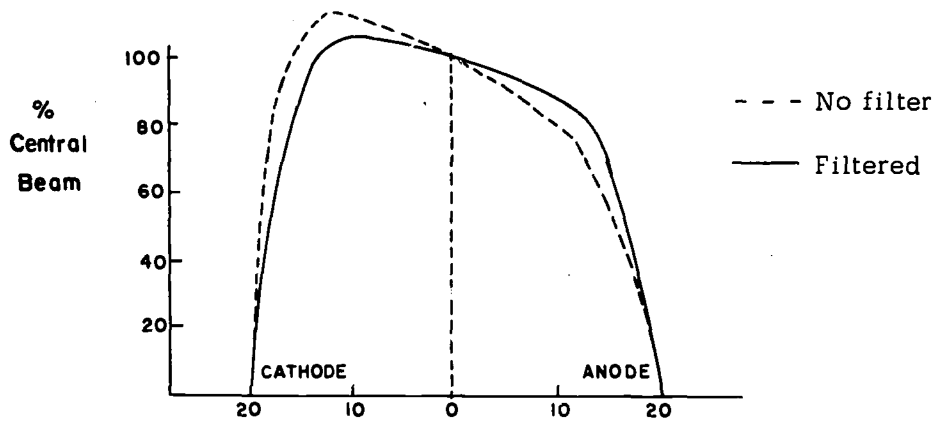


Figure 462-26 Field distribution parallel to x-ray tube axis

B. Field distribution parallel to the tube axis falls rapidly toward anode end ("heel") of target.

1. The "heel" effect is explained as follows:
   a. Not all x-rays are produced at the surface of the target.
   b. Electrons penetrate the surface and x rays are produced at a depth within target.
   c. X rays so produced are filtered by the tungsten target resulting in a loss in intensity before they emerge from the target.
   d. The thickness of tungsten increases toward the "heel" (anode end) of the target.
2. The maximum intensity not in the geometric center of field but lies on cathode side of field center.
3. The decrease in intensity with added filter is less abrupt toward anode end of the tube.

C. Field distribution perpendicular to tube axis (Fig. 462-27)

1. The distribution is uniform across the field and drops abruptly at both edges due to the beam limiting diaphragm.
2. Filtration narrows the field.

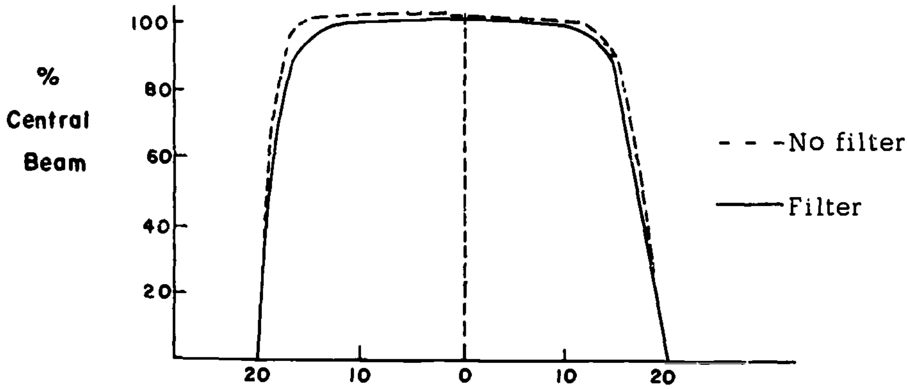


Figure 462-27 Field distribution perpendicular to x-ray tube axis

D. Target etching

1. Etching occurs when the focal spot area is raised above its recrystillation temperature.
2. Etching occurs with normal tube loadings
3. Etching results in small "pits" in target
4. Etching increases the target filtration and narrows the field.

IV. Kilovoltage

A. As electron energy is increased the direction of maximum x-ray production moves toward the direction of electron flow.

B. As a result, for a reflection target, the field distribution will change parallel to the tube axis. (Fig. 462-28)

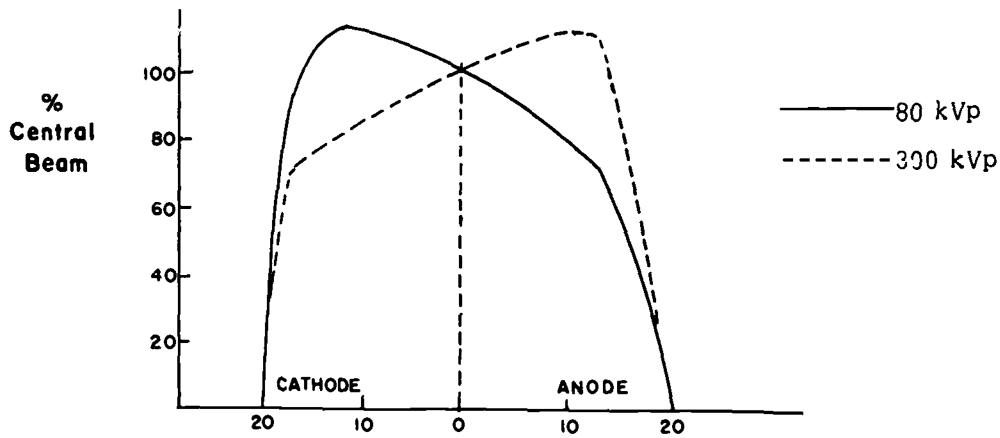


Figure 462-28 Field distribution as a function of kilovoltage

V. <u>Target Angle</u>

A. The more abrupt the target angle the greater the effect on field distribution. (Fig. 462-29)

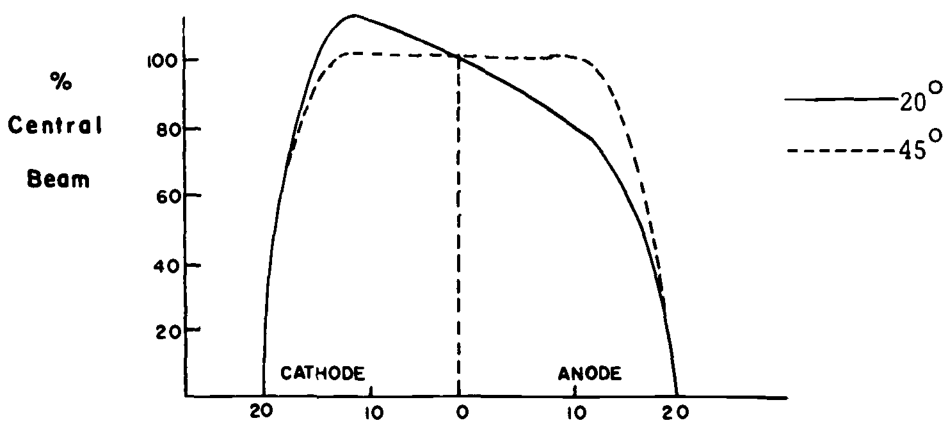


Figure 462-29 Field distribution as a function of target angle

VI. Effective Energy and Half-value Layer

A. For a monoenergetic x-ray beam with narrow beam geometry, the attenuation is given by:

1. $I = I_o e^{-\mu x}$

2. $HVL = \frac{0.693}{\mu} = \frac{0.693}{(\mu/\rho)\ \rho}$

B. Effective energy

1. Most x-ray beams are heterogeneous

2. An x-ray beam with the same HVL as a monoenergetic x-ray beam is said to have the same effective energy as the monoenergetic beam.

3. Effective energy is normally expressed as keV (eff.)

4. To determine effective energy:

a. Determine the HVL in some material (Al up to 150 kVp, Cu from 150 - 500 kVp, Pb > 500 kVp).

b. Calculate μ/ρ from $\mu/\rho = \frac{0.693}{(HVL)\ (\rho)}$

c. From a graph of μ/ρ vs photon energy determine E for μ/ρ . (Fig. 462-30)

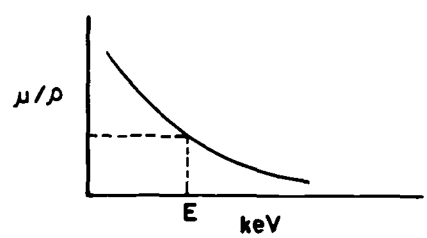


Figure 462-30 Mass attenuation coefficient vs keV

d. Example: Assume 100 kVp with HVL = 4 mm Al

1) $\mu/\rho = \frac{0.693}{(0.4\ cm)\ (2.7\ g/cm^3)} = 0.64\ cm^2/g$

2) E = 37 keV

C. The HVL has been chosen as the means to compare an x-ray spectrum with a monoenergetic x-ray beam.

1. As kVp increases, keV (eff.) increases.
2. As filtration increases, keV (eff.) increases.

VII. Determination of HVL

A. Since an x-ray beam is composed of spectrum of energies, a semilog plot of transmission vs added filter (absorber) thickness is not a straight line. (Fig. 462-31)

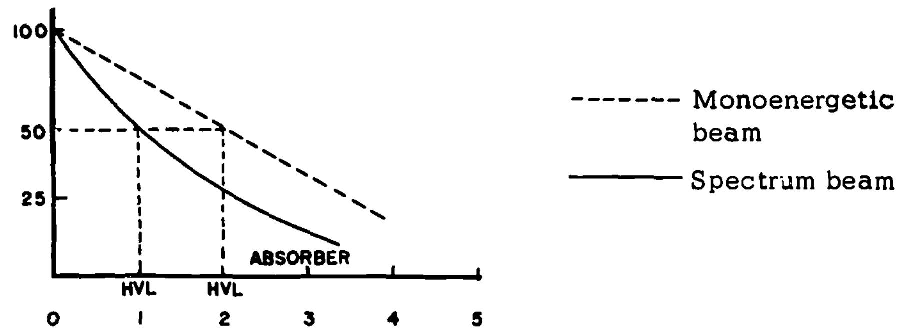


Figure 462-31 Transmission vs added absorber

1. The slope is continually changing (HVL is changing) and μ/ρ is changing.
2. The slope approaches the slope of the monoenergetic beam at high filtrations.

B. Effect of measuring geometry on HVL determinations

1. Geometric variables (Fig. 462-32)
   a. Diameter of field at absorber
   b. Source-absorber distance (SAD)
   c. Source-chamber distance (SCD)

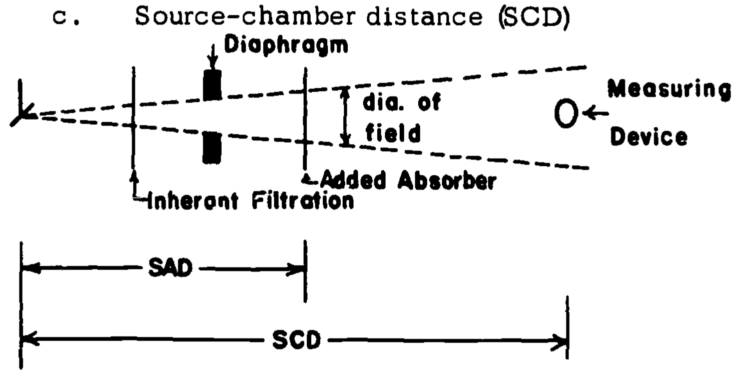


Figure 462-32 Geometric variables

2. Good geometry
   a. Narrow beam
   b. Large SCD
   c. SAD = 1/2 SCD
   d. μ/ρ is determined under good geometry
3. Poor geometry
   a. Broad beam
   b. Thick absorber
   c. Short SCD
   d. Both unattenuated and <u>scattered</u> radiation is measured
   e. Build-up factor B

      $I = I_o Be^{-\mu x}$
4. Effect of field size (Fig. 462-33)
   a. The quantity of scatter is a function of the field diameter at the added absorbers.

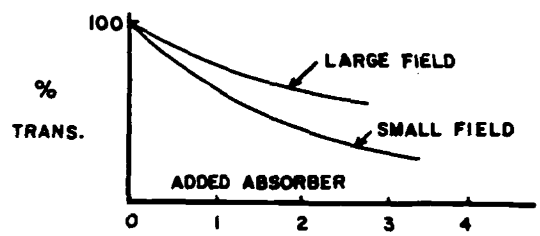


Figure 462-33 Effect of field size on measured transmission

   b. With kVp, inherent filtration and SAD constant, the HVL decreases as the diameter of the field at the added absorbers is decreased. (Fig. 462-34)
   c. The effect is due to scatter from the absorbers.

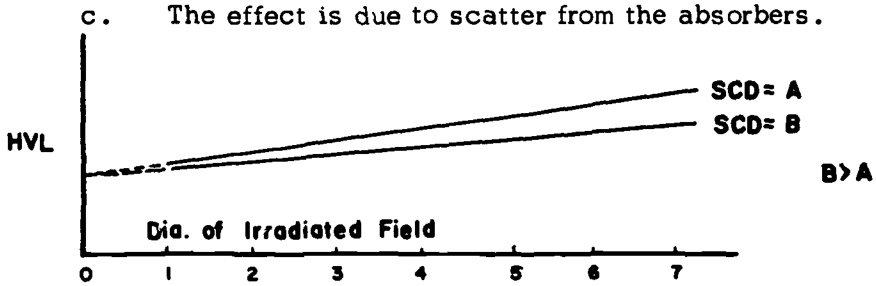


Figure 462-34 HVL vs field diameter

5. Effect of SCD

a. With kVp, inherent filtration and field diameter at irradiated absorber constant, SAD = 1/2 SCD, the HVL will decrease as the SCD is increased and level off at long SCD's. (Fig. 462-35)

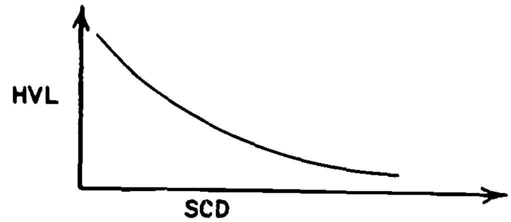


Figure 462-35 HVL vs source-chamber distance

b. At long SCD's, scatter from the absorbers becomes a lesser part of the total exposure.

6. Effect of SAD

a. With kVp, filtration, SCD and diameter of field at added absorber constant, the HVL will decrease to minimum at SAD = 1/2 SCD. (Fig. 462-36)

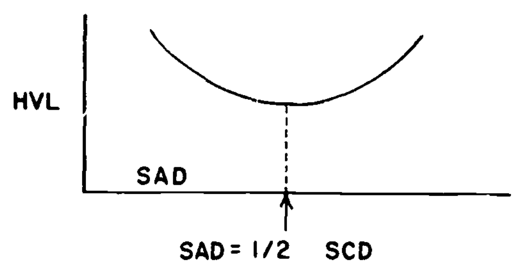


Figure 462-36 HVL vs source-absorber distance

b. The curve symetric about the minimum.

c. The curve shape is the result of scatter from the absorber.

VIII. The Unique HVL

A. Independent of measuring geometry

B. Determined by extrapolating HVL vs field diameter to zero field diameter at absorber.

1. Unique HVL is independent of geometry since the scatter is 0 at 0 field size.

2. Unique HVL used to determine keV (eff.)

C. Unique HVL can be calculated from broad beam HVL if the geometry of the determination (SAD, SCD, dia. of field) is known.

IX. The Second HVL

A. The first HVL (1 HVL) does not adequately, in itself, specify the quality of an x-ray beam.

1. The same 1 HVL can be obtained at different kVp's.

a. 200 kVp, 0.5 mm Cu, 1 HVL = 1.0 mm Cu

b. 150 kVp, 0.75 mm Cu, 1 HVL = 1.0 mm Cu

2. kVp and 1 HVL are a better description of beam quality.

3. A more complete description includes kVp, 1 HVL and second HVL (2 HVL) or homogeneity coefficient.

a. 1 HVL is the absorber thickness that reduces exposure from 100% to 50%.

b. 2 HVL is the absorber thickness that reduces exposure from 50% to 25%.

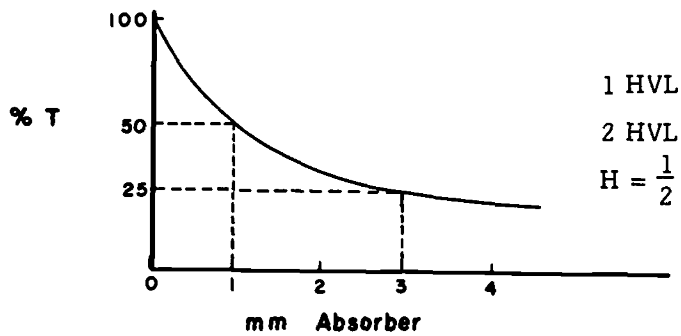
c. The homogeneity coefficient (H) is the ratio of the 1 HVL to the 2 HVL. (Fig. 462-37)

1) $H = \frac{1\ \text{HVL}}{2\ \text{HVL}} \leq 1$

2) $H_o = \frac{\text{Unique 1 HVL}}{\text{Unique 2 HVL}}$ H_o = unique homogeneity coefficient

3) $H < 1$ for a heterogeneous x-ray beam

4) $H = 1$ for a monoenergetic x-ray beam



1 HVL = 1.0 mm absorber

2 HVL = 2 mm absorber

$H = \frac{1}{2} = 0.5$

Figure 462-37 Determination of 1 HVL and 2 HVL

LECTURE NO. 9

TITLE: Personnel Monitoring Devices

PURPOSE: To discuss the different devices used for personal monitoring

TIME: One hour

VISUAL AIDS: Blackboard
Film badge and holder
Pocket chamber and charger/reader
Pocket dosimeter and charger

HANDOUTS: None

REFERENCES: Attix, Roesch and Tochilin
Radiation Dosimetry

NBS Handbook 57

Ter-Pogossian
Physical Aspects of Diagnostic Radiology

Whyte
Principles of Radiation Dosimetry

PERSONNEL MONITORING DEVICES

I. <u>Pocket Chambers and Dosimeters</u>

A. Pocket chamber with separate charger-reader

1. Operation

a. Chamber consists of a defined air volume and capacitor. The air volume is unsealed. (Fig. 462-38)

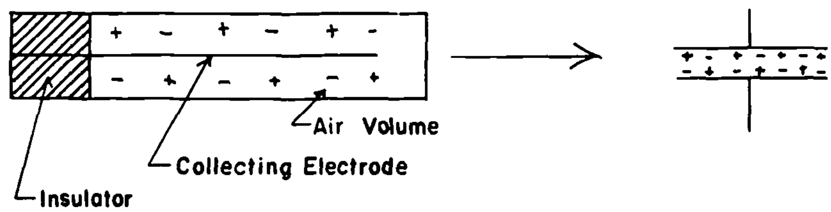


Figure 462-38 Pocket chamber

b. Ions produced cause capacitor to discharge (Fig. 462-39)

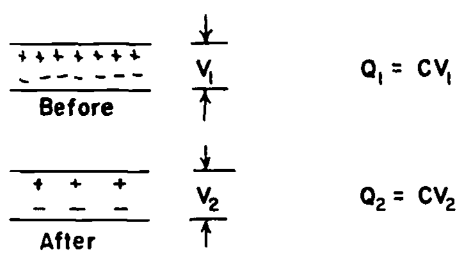


Figure 462-39 Charge on pocket chamber before and after exposure

c. Charge liberated $Q = Q_1 - Q_2 = C\ (V_1 - V_2) = C\Delta V$

d. If the chamber volume is known, exposure,

$$X = \frac{\Delta Q}{v} = \frac{C\Delta V}{v}$$

2. Cost

a. Chamber--$10 each for 0-200 mR chamber

b. Charger-reader--$500 each

B. Direct reading pocket dosimeter

1. Operation

a. Similar to pocket chamber but dosimeter includes a quartz fiber electrometer and optical system. The air volume is sealed. (Fig. 462-40)

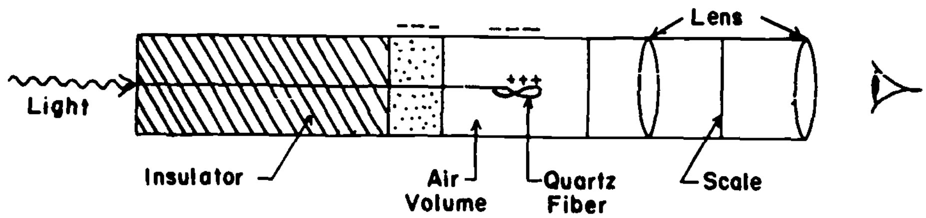


Figure 462-40 Pocket dosimeter

b. As the chamber discharges the quartz fiber "moves" and the exposure is read on the scale in mR or R

2. Cost

a. Chamber-high energy 0-200 mR--$40 each

b. Chamber-low energy 0-200 mR--$75 each

c. Charger--$50 each

C. Disadvantages

1. Chambers are subject to mechanical damage that can lead to false reading.

2. Leakage can increase the reading.

3. Readings do not provide a permanent record.

4. They are energy dependent

5. They have a limited range

D. Advantages

1. Chambers are reusable

2. The direct reader can be read "immediately"

3. They provide a daily check on exposure

II. Film

A. Operation

1. A film emulsion consists of AgBr suspended in gelatin (Fig. 462-41)

2. The photons interact with the emulsion and the resulting photoelectrons interact with the AgBr crystals.

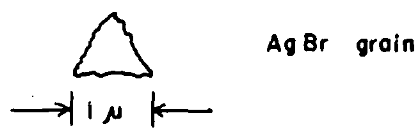


Figure 462-41 AgBr grain

3. Photoelectron renders grain susceptable to developer (latent image) and developer supplies electrons to convert silver ions to free silver

$$(Ag^{+})\ (Br^{-}) + e^{-} \rightarrow Ag + Br^{-}$$

B. Characteristics

1. Single hit phenomena (direct exposure)

   a. It takes only one photon (X or γ) "hit" to produce the latent image in a grain

   b. Therefore the process is not rate dependent

   c. There is a linear relation between response (density) and exposure (Fig. 462-42)

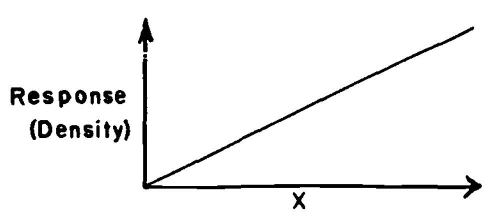


Figure 462-42 Film response vs exposure

d. For light (intensifying screens) exposures it requires several photons to produce the latent image, therefore this process is rate dependent.

2. Advantages of film:
   a. It can integrate exposure over a long time
   b. Relatively low in cost ($0.50 - $2.00)
   c. Provides a permanent record
   d. It is rate independent (within limits)
   e. It is easy to use
   f. It is relatively rugged

3. Disadvantages of film:
   a. Processing time is required
   b. Response influenced by humidity and chemical actions

4. Sensitivity

Source	Min. Sensitivity
Diagnostic x rays	~ 5 mR
γ or high energy x rays	~ 20 mR

5. Energy dependence (Fig. 462-43)

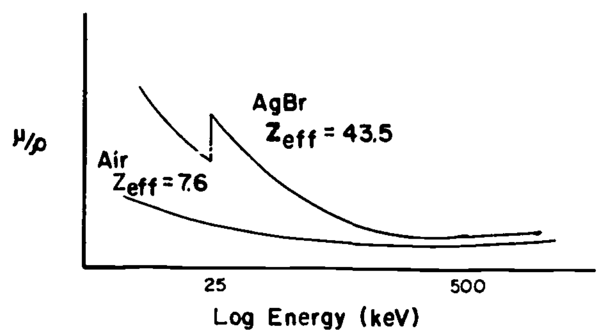


Figure 462-43 Mass attenuation coefficient vs keV for film and air

   a. AgBr has greater sensitivity than air at lower energies

b. Relative sensitivity is the reciprocal of the exposure required to produce a certain density (1.0) (Fig. 462-44)

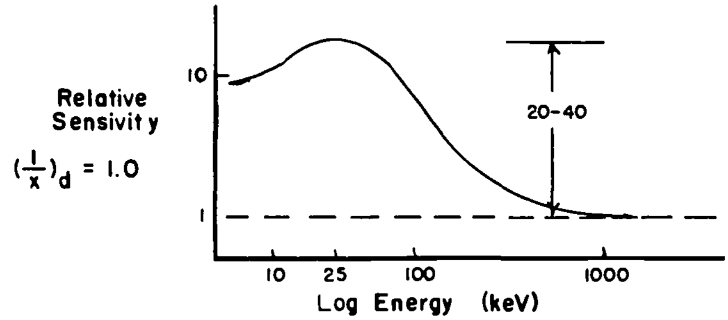


Figure 462-44 Relative film sensitivity vs keV

1) If X = 1R for d = 1.0 at 25 keV, then 20-40R are needed for d = 1.0 at 1MeV

2) Rule of thumb--keV = 1/2 kVp for a heavily filtered x-ray beam.

3) Peak in the curve corresponds to the K-edge of AgBr

6. Film density

a. A densitometer used to measure film density. It measures the light transmitted through the film (Fig. 462-45)

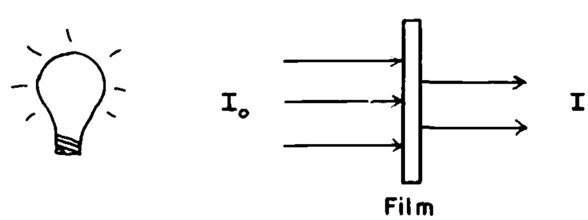


Figure 462-45 Transmission of light through film

b. Transmission $T = \frac{I}{I_o}$

c. Density $= \log_{10} \frac{1}{T} = \log_{10} \frac{I_o}{I}$

Transmission		Density
1/10	(10^{-1})	$\log_{10} 10 = 1$
1/100	(10^{-2})	$\log_{10} 100 = 2$
1/1000	(10^{-3})	$\log_{10} 1000 = 3$
1/1000000	(10^{-6})	$\log_{10} 10^6 = 6$

d. Density $\propto$ number of grains developed

7. Sensitometric curves

a. Used to relate density to exposure (X)

b. Linear relation between density and exposure (Fig. 462-46)

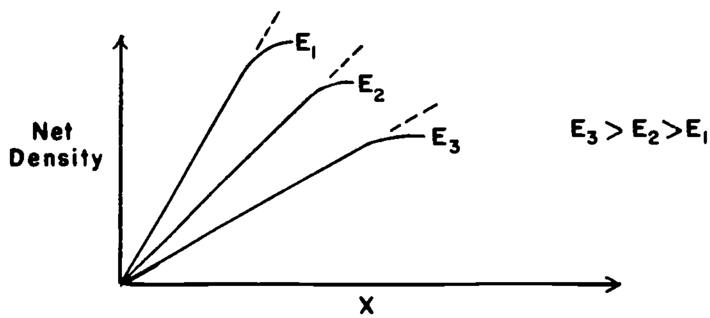


Figure 462-46. Film response vs exposure for several photon energies

1) Net density is the density of the exposed film minus the density of the unexposed film.

2) A family of curves results due to energy dependence of the AgBr

3) The deviation from linear at high exposures is due to photoelectrons acting on grains which already have produced the latent image ("run out of film")

c. H & D curve (Hurter and Driffield 1890)--net density vs log X (Fig. 462-47)

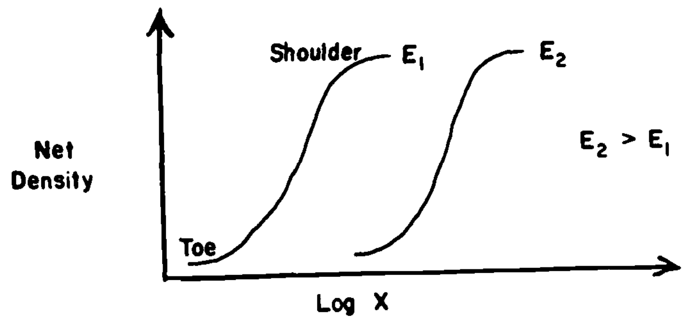


Figure 462-47 H and D curves

1) The shape of the curve remains the same as function of energy but the curve is shifted on exposure axis
2) H and D curves are most often used to represent the response of film

d. Log net density vs log X (Fig. 462-48)

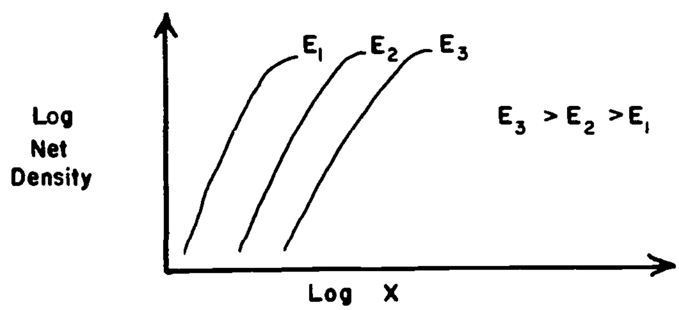


Figure 462-48 Log net density vs log exposure

1) This presentation is useful when a wide range of exposures are of interest.
2) It is easier to read (graphically) extreme densities.

8. For a given emulsion or film type the shape of the curves is a function of:
   a. Developing time
   b. Developer temperature
   c. Developer condition

C. Calibration and use
1. Procedure
   a. Calibration films, control and badge films are taken from the same batch (emulsion number).
   b. All films are processed together
2. Film badge
   a. Serves as holder for the film
   b. It contains several filters
      1) Consider 2 films, one exposed to heavily filtered 50 kVp x rays and one to radium gamma rays (1MeV)
      2) If both films are assumed to have been exposed by the same energy photons, a gross over or under evaluation of the exposure from one of the films will be obtained (Fig. 462-49)

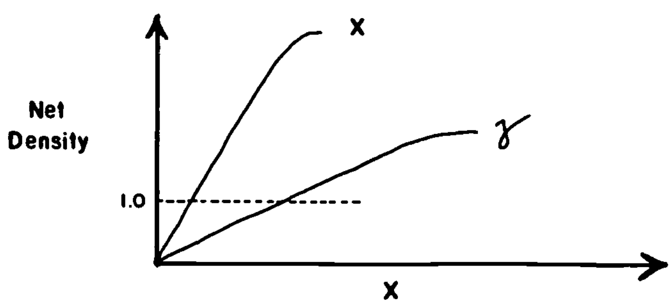


Figure 462-49 Net density vs exposure for film exposed to x rays and gamma rays

3) Filters (usually 3) in the film badge holder compensate for the energy dependence of the film.

a) Open window, no filter, film density is due primarily to low energy x rays

b) Filter areas absorb low energy x rays and transmit higher energies. This permits evaluation of energy and the total exposure

4) Film works on the photoelectric effect

$\propto \frac{Z^n}{E^x}$ so as E $\downarrow$, d $\uparrow$

III. Thermoluminescent Dosimeters

Thermoluminescent materials are being used for personnel monitoring to either replace or augment personal monitoring film. These materials will be discussed in a later lecture.

LECTURE NO. 10

TITLE: Chemical Dosimetry

PURPOSE: To discuss several chemical dosimeters and their theory of operation

TIME: One hour

VISUAL AIDS: Blackboard

HANDOUTS: None

REFERENCES:

Attix, Roesch and Tochilin
Radiation Dosimetry

Chorzempa
Ionizing Radiation and its Chemical Effects: A Historical Study of Chemical Dosimetry (1902-1962)

Hine and Brownell
Radiation Dosimetry

Spiers and Reed
Radiation Dosimetry

CHEMICAL DOSIMETRY

I. Introduction

The basis for chemical dosimetry is the determination of dose by the magnitude and kind of a chemical change that is produced in a medium. Most chemical dosimeters involve reactions produced in aqueous solutions and have a principal use in the high dosage range.

II. Desirable Characteristics

A. High sensitivity

B. Accuracy

C. Reproducibility, linearity

D. Stable - time and temperature

E. Wide range of physical forms

F. Inexpensive

G. Energy independent

H. Tissue equivalent

III. Basic Considerations

A. Absorption of energy in a liquid system produces a definite chemical reaction.

1. Consider the chemical change.

2. Relate the energy deposited and ionization produced to a chemical effect.

3. "Good" or "bad" effects in a physical system can result from chemical change.

4. The quantity of chemical change should increase linearly with dose.

B. Reaction yield

1. Expressed as number of molecules of specified substance formed or destroyed per ion pair produced.

2. G value - number of molecules altered chemically per 100 eV absorbed.

   a. Value of 100 - 200 is required for doses of 100 - 1000 rad.

   b. Chain reactions are normally required for high G values.

3. Use is limited by the chemical method of analysis used to detect the newly formed compound.

4. Absorbed dose given by:

   a. $D_{rad} = \dfrac{(M)\ (9.64 \times 10^{8})}{(G)\ (P)\ \rho}$

      1) M = number of moles of ion product P

      2) (G) (P) = G value of ion product P

      3) ρ = density of system

5. The foremost problem is that a very pure system is required.

C. Irradiation of water

1. Some products formed are free radicals (contain unpaired electron in outer shell).

2. A primary chemical bond is represented as the sharing of two electrons between constituent atoms.

3. Radiolysis of water

   a. $H_2O \rightarrow H_2O^+ + e^-$

   b. $H_2O^+ \rightarrow H^+ + OH^{\cdot}$

   c. $e^- + H_2O \rightarrow H_2O^-$

   d. $H_2O \rightarrow H^{\cdot} + OH^-$

   e. Overall $H_2O \rightarrow H^{\cdot} + OH^{\cdot}$

IV. <u>Typical Chemical Dosimeters</u>

A. Ferrous sulfate (Fricke Dosimeter)

1. Ferrous ions (Fe^{++}) are converted to ferric ions (Fe^{+++})

2. Chemical reactions

   a. $H^{\cdot} + O_2 \rightarrow HO_2^{\cdot}$

b. $Fe^{++} + OH^{\cdot} \rightarrow Fe^{+++} + OH^{-}$

c. $Fe^{++} + HO_2^{\cdot} \rightarrow Fe^{+++} + HO_2^{-}$

d. $HO_2^{-} + H^{+} \rightarrow H_2O_2$

e. $H_2O_2 + Fe^{++} \rightarrow Fe^{+++} + OH^{\cdot} + OH^{-}$

3. The quantity of Fe^{+++} is determined by absorption spectroscopy or chemical titration

4. The useful dose range is $10^3 - 10^5$ rads $(G < 20)$

B. Ceric sulfate

1. Reduction of ceric (Ce^{4+}) to cerous ion (Ce^{3+})

2. It is very sensitive to impurities

3. The useful range is $10^4 - 10^8$ rad $(G > 5)$

C. Chlorinated hydrocarbons

1. Production of HCL is determined

2. It is a high yield reaction and suitable for lower doses $(> 20$ rad)

3. A dye indicator is used to determine the quantity of HCL produced.

LECTURE NO. 11

TITLE: Thermoluminescent Dosimeters

PURPOSE: To present the fundamentals of thermoluminescent phosphors and their uses as ionizing radiation dosimeters

TIME: One hour

VISUAL AIDS: Blackboard
E. G. & G. thermoluminescent dosimeters

HANDOUTS: None

REFERENCES: Attix, Roesch and Tochilin
Radiation Dosimetry

Cameron, Suntharalingam and Kenney
Thermoluminescent Dosimetry

Fowler
Solid State Dosimetry

THERMOLUMINESCENT DOSIMETERS

I. Introduction

The basis for use of some materials as dosimeters is their ability to store energy imparted to them by radiation. The release of this energy in the form of light may be controlled and measured and the quantity of light is approximately a linear function of absorbed energy.

II. Theory

A. Definitions

1. Fluorescence - glow of certain crystals immediately following exposure to electromagnetic or particulate radiation.
2. Phosphorescence - a time lag between exposure and emission of light
3. Thermoluminescence - electrons trapped at metastable levels in crystal defects or freed by thermal stimulation resulting in release of light
4. Phosphors - crystals exhibiting any of the above characteristics

B. Physical model of a phosphor (Fig. 462-50

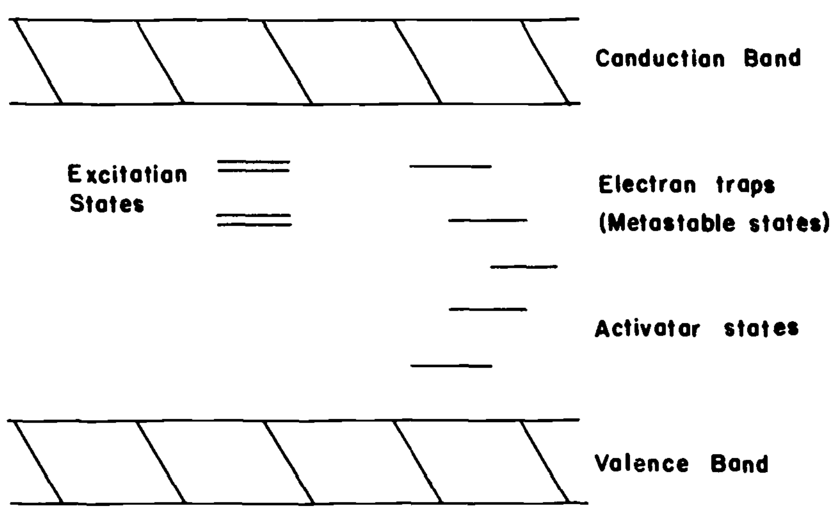


Figure 462-50 Physical model of a phosphor

1. Based on energy band scheme of a pure insulator
2. Impurity atoms produce metastable states between valence and conduction bands
3. Electrons raised to conduction band may become associated with one of these energy states and said to be "trapped".

III. Characteristics of TL Materials

A. Consider CaF_2:Mn, Lif (TLD-100)

B. Criteria

1. Sensitivity (x and γ)
   a. Lower limit of LiF is 10 mR ± 25% (requires special readout)
   b. CaF_2 and $CaSO_4$ are more sensitive with $CaSO_4$:Mn in μ R range
   c. Factors determining detectable limits
      1) Detector (PM tube) dark current
      2) Non-radiation induced TL
      3) Thermal interference from heater
      4) Wavelength of emitted light
2. Response
   a. LiF is linear from 10^{-2} - 10^{3} R, supra-lineal above 10^{3} R, and useful to 10^{5} R.
   b. CaF_2 is approximately linear to 10^{6} R
   c. $CaSO_4$ is linear to 10^{3} - 10^{4} R
3. Rate dependence

   LiF is independent of rate to 10^{8} R/sec.

4. Energy dependence (Fig. 462-51)

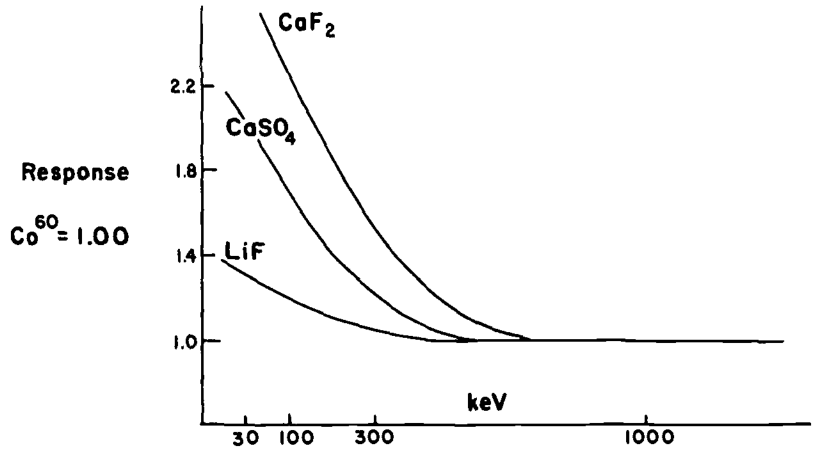


Figure 462-51 Energy dependence of TL phosphors

a. LiF response at 30 keV is only 25% greater than that at 1.2 Mev.

b. CaF_2 response ~ 13 times greater at 40 keV than at 1.2 Mev.

c. $CaSO_4$ response ~ 11 times greater at 40 keV than at 1.2 Mev.

d. Filters are used to "flatten" response.

5. Energy storage capability (decay)

a. LiF fades 5%/yr at $22^{\circ}C$, 15 - 20%/yr at $37^{\circ}C$

b. CaF_2 fades more rapidly than LiF

c. $CaSO_4$ fades fast

IV. <u>Equipment</u>

A. Readout

1. Heat phosphor

2. Measure light emitted

3. Display results

a. Digital system

b. Strip charter recorder - Light (PM current) vs temperature (time)

B. Miscellaneous

1. Annealing oven (50 - 450°C)

2. Phosphor dispensor

C. TL material

V. LiF Material in Powder Form

A. Characteristics

1. White crystalline powder

2. Inert

3. Non-toxic

B. Sieve (80 - 200 mesh)

C. Anneal

400°C for 1 hr, 80°C for 24 hrs

D. Expose

E. After exposure, dispense and read samples

1. Samples are generally 20 - 50 mg

2. Readout time is 6 - 60 sec at 300°C

3. 1 - 3% reproducibility for $X > 1$ R in lab use

F. Precautions in use

1. Different equipment will not produce the same sensitivity.

2. Recalibrate powder after use.

3. Dispense powder accurately.

4. Maintain uniform crystal distribution in heating pan.

VI. <u>LiF and CaF_2: Mn Dosimeters</u>

A. Evacuated (or inert gas filled) glass envelope

1. TL powder is bonded to support or hot pressed to support.

2. Tungsten filament heating element is used.

B. Glass or plastic tubes

1. Heated by induction

2. Can be small (~ 1 mm dia x 6 - 12 mm long)

C. Hot-press material (no outer container)

D. Advantages of dosimeters over loose powder

1. Easy and convenient readout
2. Easy to handle
3. No need to sieve or clean
4. No phosphor loss
5. Lower useful dose range
6. Easy to incorporate in dosimeter (energy compensating) holders
7. Easy to sterilize (glass)

LECTURE NO. 12

TITLE: Correlation of Exposure and Absorbed Dose

PURPOSE: To determine the energy absorbed in matter from an exposure to x rays

TIME: One hour

VISUAL AIDS: Blackboard

HANDOUTS: None

REFERENCES: Attix, Roesch and Tochilin
Radiation Dosimetry

ICRU Report 10b

Johns and Cunningham
The Physics of Radiology

Ter-Pogossian
Physical Aspects of Diagnostic Radiology

Whyte
Principles of Radiation Dosimetry

CORRELATION OF EXPOSURE AND ABSORBED DOSE

I. Introduction

The biological effect that ionizing radiation is capable of producing is due to the energy that is absorbed in tissue. Exposure, measured in roentgens, tells nothing about absorbed energy. The air exposure value must be converted to an absorbed dose (in rads) to evaluate the biological effect.

II. Units and Constants

A. Exposure $X = \Delta Q/\Delta m$

Defined in air for x or γ radiation only

B. Absorbed dose $D = \Delta E/\Delta m$

1. Defined in any material for any ionizing radiation
2. Unit of absorbed dose is the rad, 1 rad = 100 ergs/g

C. Constants

1. Charge of an electron
   a. 1.6×10^{-19} coulombs
   b. 4.8×10^{-10} esu
2. 1.6×10^{-12} ergs/esu
3. Average energy (W) expended by electrons in producing an ion pair:
   a. $W_{air} = 33.7$ eV/ion pair $= 5.4 \times 10^{-11}$ erg/ion pair

III. Absorbed Dose in Air

A. Relation between the roentgen and the rad:

1. $$1\text{ R} = \left[\frac{1\text{ esu}}{0.001293\text{ g}}\right]\left[\frac{33.7\text{ eV}}{\text{ip}}\right]\left[\frac{1\text{ ip}}{4.8 \times 10^{-10}\text{ esu}}\right]\left[\frac{1.6 \times 10^{-12}\text{ ergs}}{\text{eV}}\right]\left[\frac{1\text{ rad}}{100\text{ ergs/g}}\right]$$

$$1\text{ R} = 0.87\text{ (rad)}$$

B. Relation between dose and exposure:

1. $$D_{air} = X \ (R) \left[\frac{0.87 \text{ rad}}{1 \text{ R}}\right]$$

$$D_{air} = 0.87 \ X \ (\text{rad})$$

IV. <u>Absorbed Dose in Materials Other Than Air</u>

A. Calibrated ion chamber used (Fig. 462-52)

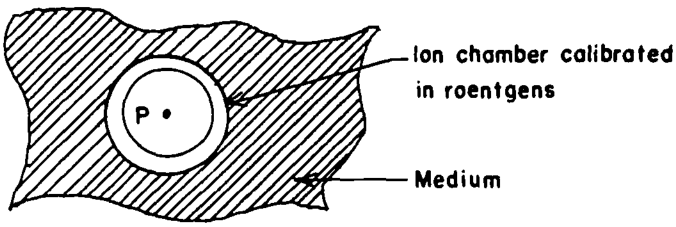


Figure 462-52 Determination of Absorbed Dose

1. We want to determine absorbed dose at P
2. Place an ion chamber in the medium with the chamber center at P.
3. Since the medium and the air in the ion chamber are exposed to the same radiation field, the fraction of incident energy absorbed in each case is proportional to the mass energy absorption coefficient μ_{en}/ρ of the medium and of air.

a. $$\frac{D_{med}}{D_{air}} = \frac{(\mu_{en}/\rho)_{med}}{(\mu_{en}/\rho)_{air}}$$

b. $$D_{air} = 0.87 \ X$$

c. $$D_{med} = 0.87 \ X \ \frac{(\mu_{en}/\rho)_{med}}{(\mu_{en}/\rho)_{air}}$$

d. $$f = 0.87 \ \frac{(\mu_{en}/\rho)_{med}}{(\mu_{en}/\rho)_{air}}$$

e. $$D_{med} = f \ X \ \text{rads}$$

4. Example: An air wall chamber placed in muscle tissue reads 1 R when exposed to 100 keV photons. What is absorbed dose?

   a. $D_{muscle} = (f_{muscle})\ (X)$

   $= (0.948)\ (1)$

   $= 0.948$ rad

B. Calibrated chamber not available

1. Use a chamber of known volume and wall composition.
2. The chamber must satisfy Bragg-Gray cavity theory:
   a. Secondary electron equilibrium must be maintained (equilibrium wall thickness).
   b. Only a small fraction of the secondary electron energy is dissipated in cavity (cavity must be small).
   c. There must be negligible photon absorption by the cavity (particles set in motion in cavity arise from interactions in chamber wall).
3. If the cavity satisfied Braff-Gray theory, the dose in the chamber wall is:
   a. $D_w = S_a^w D_a$ where a refers to the air cavity.
   b. Since different materials are ionized to different degrees by the same energy electrons, an electron of a given energy produces a different number of ions in the gas than in an equal mass of wall material. S_a^w expresses the ratio between these two numbers and is called the stopping power ratio.

$$S_a^w = \frac{\text{energy imparted to unit mass of wall material by electrons}}{\text{energy imparted to unit mass of air by same electron flux}}$$

c. If J_a = number of ion pairs produced per gram of air and W_a = the average energy required to produce an ion pair then:

1) $D_a = J_a W_a$

a) J_a = ion pairs/g

b) W_a = ergs/ion pair

2) $\therefore D_w = S^w_a J_a W_a$

3) If the wall material is air $S^w_a = 1$ and

$D_w = D_a = J_a W_a$

4) Example: Let Q = charge collected in esu and v = chamber air volume in cm^3.

a) $$J_a = \frac{Q\ (esu)\quad (1\ ion\ pair)\quad (1\ cm^3)}{v\ (cm^3)\quad (4.8 \times 10^{-10}\ esu)\quad (0.001293g)}$$

$$= \frac{Q}{v}\ (1.6 \times 10^{12}\ ion\ pair/g)$$

b) For air $X = \frac{Q}{v}$

c) $J_a = (X)\ (1.6 \times 10^{12}\ ion\ pair/g)$

d) $$D_a = (X)\ (1.6 \times 10^{12}\ ion\ pair/g)\ (5.4 \times 10^{-11}\ erg/ip)$$

$$= (X)\ (0.87 \times 10^{2}\ ergs/g)$$

$$= 0.87\ X\ rad$$

d. The energy absorbed in the medium may be determined from that absorbed in the cavity wall (since cavity is small) by the ratio of the mass energy absorption coefficients.

$$D_m = D_w \frac{(\mu_{en}/\rho)_m}{(\mu_{en}/\rho)_w}$$

e. Another means is to insert a Bragg-Gray cavity in the material (same as letting the medium replace chamber wall).

1) $D_w = S_a^w D_a$

2) $w \rightarrow m$

3) $D_m = S_w^m D_a$

LECTURE NO. 13

TITLE:	X-Ray Shielding
PURPOSE:	To present methods for the determination of protective barrier thickness for x-ray installations up to 10 MeV
TIME:	One hour
VISUAL AIDS:	Blackboard
HANDOUTS:	None
REFERENCES:	Braestrup and Wyckoff <u>Radiation Protection</u>
	ICRP Publication 3
	ICRP Publication 15
	NBS Handbook 93
	NCRP Report 33
	NCRP Report 34
	NCRP Report 35
	Radiological Health Handbook

X-RAY SHIELDING

I. Introduction

A. Narrow beam attenuation of a monoenergetic x-ray beam can be expressed as:

$I = I_o e^{-\mu x}$ Where: I_o = initial intensity at point of interest

I = intensity at point of interest after attenuating material placed in beam

e = base of natural logarithm

μ = linear absorption coefficient of attenuating material

x = thickness of attenuating material

B. Broad beam attenuation of a monoenergetic x-ray beam can be expressed as:

$I = I_o B e^{-\mu x}$ Where: B = build-up factor

C. For a monoenergetic x-ray beam, it is a relatively simple matter to compute the thickness of material necessary to reduce the intensity at a point to a given level.

D. However, when designing the shielding requirements for x-ray installations, these simple mathematical relationships cannot be applied.

E. Factors determining the thickness of protective barrier necessary to reduce the x-ray exposure to a given level depends upon the:

1. Quality of radiation produced
2. Quantity of radiation produced in a given time period
3. Distance from x-ray tube to area of interest
4. Degree and nature of occupancy of the area
5. Type of area
6. Material to be used

II. Definitions

A. Protective barrier: barrier of attenuating materials used to reduce radiation exposure.

B. Primary protective barrier: barrier sufficient to attenuate the useful beam to the required degree.

C. Secondary protective barrier: barrier sufficient to attenuate stray radiation to the required degree.

D. Stray radiation: radiation not serving any useful purpose. It includes leakage and secondary radiation.

E. Controlled area: a defined area in which the occupational exposure of personnel to radiation or to radioactive material is under the supervision of an individual in charge of radiation protection. (This implies that a controlled area is one that requires control of access, occupancy, and working conditions for radiation protection purposes.)

F. Uncontrolled area: all areas not specified as being controlled.

G. Diagnostic-type protective tube housing: x-ray tube housing so constructed that the leakage radiation at a distance of 1 meter from the target cannot exceed 100 mR in 1 hour when the tube is operated at any of its specified ratings.

H. Therapeutic-type protective tube housing: x-ray tube housing so constructed that the leakage radiation at a distance of 1 meter from the target cannot exceed 1 R in 1 hour and at a distance of 5 cm from any point on the surface of the housing accessible to the patient cannot exceed 30 R in 1 hour when the tube is operated at any of its specified ratings.

I. Occupancy factor (T): the factor by which the workload should be multiplied to correct for the degree or type of occupancy of the area in question.

J. Use factor (U): the fraction of the workload during which the useful beam is pointed in the direction under consideration.

K. Workload (W): the use of an x-ray machine expressed milliampere minutes per week.

III. Determination of Protective Barrier Thickness

A. Primary protective barrier requirements

It has been found experimentally that:

1. The transmission of x ray through thick barriers is closely related to the peak voltage of the x-ray tube.
2. Barrier thickness at a given kV is essentially independent of changes in HVL caused by the added filtration in the machine.
3. At any given kV and with minimum added filtration, the exposure rate produced by any x-ray machine is nearly a constant when expressed in terms of roentgens per mA-min at a distance of one meter.

B. For purposes of determining barrier thicknesses, transmission curves have been determined for various tube voltages and attenuating materials.

1. The ordinate of the transmission curve is the transmitted exposure per mA-min at a reference distance of one meter and is given the symbol K.
2. To compute the required barrier thickness for any set of parameters, determine allowed value of K and find the corresponding thickness on the appropriate attenuation curve.
3. The value of K is computed from:

$$K_{ux} = \frac{P\,(d_{pri})^2}{WUT}$$

Where: K_{ux} = R/mA - min at one meter

P	= maximum permissible exposure for design purposes: controlled areas= 0.1 R/wk, uncontrolled areas = 0.01 R/wk
d_{pri}	= distance from x-ray target to area, meters
W	= workload, mA-min/wk
U	= use factor
T	= occupancy factor

C. If one wishes to use materials for which no attenuation data are available, their equivalents can be determined on the basis of density alone.

Example:

1.0 inch sand plaster $(\frac{1.54}{2.35})$ = .65 inch concrete

ρ sand plaster = 1.54 g/cc

ρ concrete = 2.35 g/cc

D. Secondary protective barrier

1. Barriers that are exposed only to leakage and scattered radiation.
2. Since leakage and scatter may be of significantly different qualities, their barrier requirements must be computed separately.
3. Scattered radiation. For design purposes it may be assumed that:
   a. The ratio, a, of 90^{o} scattered exposure to incident exposure is 10^{-3} up to 3 Mev.
   b. The 90^{o} scattered radiation generated by a useful beam produced at a potential of 500 kV and below is, to a first approximation assumed to have the same average energy as the useful beam.

c. The 90° scattered radiation generated by a useful beam produced at a potential greater than 500 kV is, to a first approximation, equivalent in energy distribution to x rays generated by a potential of 500 kV regardless of the kilovoltage of the useful beam.

d. The scattered exposure is a linear function of the field area, F, at the scatterer.

e. For tube potentials of 500 kVp or less, the value of K is computed from:

$$K_{ux} = \frac{P}{a\,W\,T} \quad (d_{sca})^2 \; (d_{sec})^2 \quad \frac{400}{F}$$

Where: K_{ux} = R/mA - min at one meter

P = maximum permissible exposure for design purposes

a = ratio of scatter to incident exposure (10^{-3})

W = workload, mA - min/wk

T = occupancy factor

d_{sca} = distance from radiation source to scatterer, meters

d_{sec} = distance from radiation source to area, meters

F = area of useful beam at scatterer, cm^2

f. For tube potentials of 1, 2 and 3 Mev the equation is modified, due to the higher output, by multiplying the right-hand side by 1/20 for 1 Mev, 1/300 for 2 Mev and 1/700 for 3 Mev.

4. Leakage radiation

a. The leakage radiation is highly filtered. The number of half-value layers required in the secondary barrier for leakage radiation depends upon:

1) The tube housing type.

2) Tube maximum operating potential.

3) Weekly operating time.

4) Distance to occupied area.

5) Occupancy of area.

6) Permissible exposure per week.

b. The transmission factor for diagnostic-type protective tube housing is given by $B_{lx} = \frac{(P)\,(d_{sec})^2\,(600I)}{W\,T}$ and for therapeutic-type protective tube housings 500 kVp and below by $B_{lx} = \frac{(P)\,(d_{sec})^2\,(60I)}{W\,T}$ where P, d_{sec}, W and T are as defined previously, B_{lx} is the transmission factor and I is the maximum continuous tube current.

c. The leakage barrier thickness, S_L, is then computed by $S_L = N\,(HVL)$ where N is the number of half-value layers corresponding to a transmission of B_{lx}, and HVL is the numerical value of the half-value layer.

E. Total secondary barrier requirements

1. If the required barriers for leakage and scattered radiation are found to be approximately the same, one HVL should be added to the larger one to obtain the required total secondary barrier thickness.

2. If the two differ by at least three HVL's, the thicker of the two will be adequate.

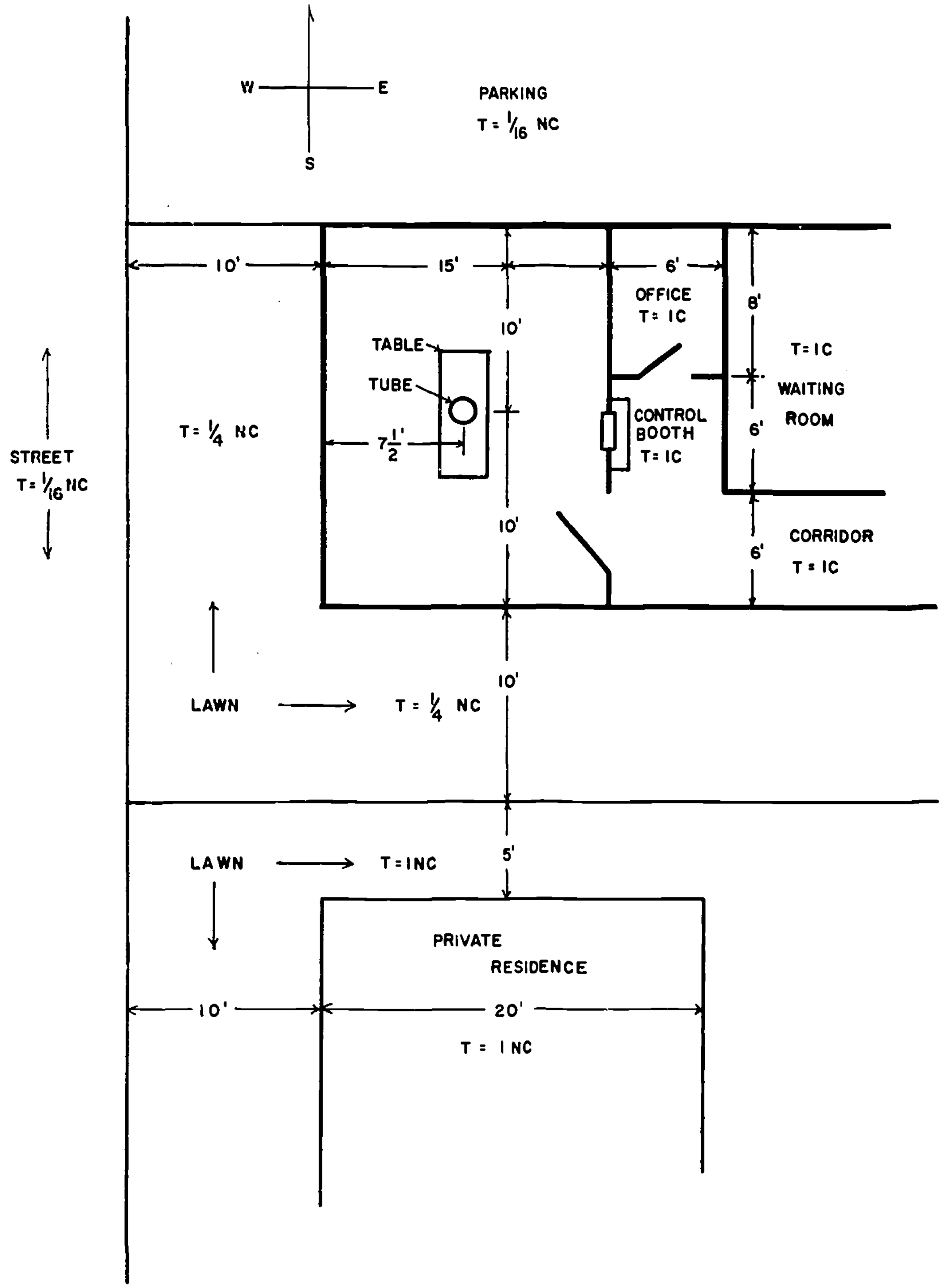
SHIELDING DESIGN PROBLEM SET

GIVEN:

1. The attached plan (Fig. 461 - 53) of a proposed installation.
2. The building is a single-story structure on grade.
   a. No basement--earth fill.
   b. Roof above (12' floor to roof level) with T = 1/16 noncontrolled.
3. A 200 kVp, 30 mA therapeutic x-ray unit is to be installed.
4. The x-ray tube will be located as shown on the plan.
5. The useful beam will be directed at the floor (U = 1) and north wall (U = 1/4) only.
6. W = 10,000 mA - min/wk.
7. Occupancy factors as shown on the plan (C = controlled area, NC = noncontrolled area).
8. Broad beam lead attenuation data attached.
9. HVL vs percent transmission data attached.
10. The HVL for 200 kVp is 0.48 mm Pb.

REQUIRED: Compute, in lead, the shielding required for this installation.

Figure 461 - 53



ANSWERS TO SHIELDING DESIGN PROBLEM SET

1. Type and degree of adjacent area occupancy

Area	Type/Degree	Design Max. mR/wk
Parking, N	Noncontrolled / 1/16	160
Lawn, W & S	Noncontrolled / 1/4	40
Street, W	Noncontrolled / 1/16	160
Private lawn, S	Noncontrolled / 1	10
Residence, S	Noncontrolled / 1	10
Roof	Noncontrolled / 1/16	160
Corridor, control, Office, waiting room	Controlled / 1	100

2. Shielding calculations

   a. North wall

      1) Primary barrier. P = 0.01 R/wk, d = 10' (3.05 m),

      W = 10,000 mA - min/wk, U = 1/4, T = 1/16

$$K = \frac{(0.01)\ (3.05)^2}{(10^4)\ (1/4)\ (1/16)} = 0.000595 \rightarrow 3.3 \text{ mm Pb}$$

2) Secondary barrier, $d_{sca} = 0.5$ m, I = 30 mA, F = 400 cm^2

Scatter $K = \frac{0.01}{(10^{-3})(10^4)(1/16)} (3.05)^2 (0.5)^2$

$= 0.037 \rightarrow 1.1$ mm Pb

Leakage $B = \frac{(0.01)(3.05)^2 (60)(30)}{(10^4)(1/16)}$

$= 0.27 \rightarrow 1.9$ HVL $\rightarrow 0.91$ mm Pb

Total secondary $1.1 + 0.48 = 1.58$ mm Pb

b. East wall and door

1) Secondary scatter, P = 0.1 R/wk, $d_{sec} = 7\ 1/2'$ (2.29 m)

W = 10,000 mA - min/wk, T = 1 , $d_{sca} = 0.5$ m, F = 400 cm^2

$K = \frac{0.1}{(10^{-3})(10^4)(1)} (3.29)^2 (0.5)^2 \frac{(400)}{(400)}$

$= 0.0131 \rightarrow 1.5$ mm Pb

2) Secondary leakage, I = 30 mA

$B = \frac{(0.1)(2.29)^2 (60)(30)}{(10^4)(1)}$

$= 0.094 \rightarrow 3.45$ HVL's $\rightarrow 1.65$ mm Pb

3) Total secondary $1.65 + 0.48 = 2.13$ mm Pb

c. South wall

1) Secondary scatter, P = 0.01 R/wk, $d_{sec} = 10'$ (3.05 m)

W = 10,000 mA - min/wk, T = 1/4, $d_{sca} = 0.5$ m, F = 400 cm^2

$K = \frac{0.01}{(10^{-3})(10^4)(1/4)} (3.05)^2 (0.5)^2 \frac{(400)}{(400)}$

$= 0.0093 \rightarrow 1.7$ mm Pb

2) Secondary leakage, I = 30 mA

$$B = \frac{(0.01)\ (3.05)^2\ (60)\ (30)}{(10^4)\ (1/4)}$$

$= 0.067 \rightarrow 3.9$ HVL's $\rightarrow 1.87$ mm Pb

3) Total secondary $1.87 + 0.48 = 2.35$ mm Pb

d. West wall

1) Secondary scatter, P = 0.01 R/wk, d_{sec} = 7 1/2' (2.29 m)

W = 10,000 mA-min/wk, T = 1/4, d_{sca} = 0.5 m, F = 400 cm^2

$$K = \frac{0.01}{(10^{-3})\ (10^4)\ (1/4)}\ (2.29)^2\ (0.5)^2\ \frac{(400)}{(400)}$$

$= 0.00524 \rightarrow 1.95$ mm Pb

2) Secondary leakage, I = 30 mA

$$B = \frac{(0.01)\ (2.29)^2\ (60)\ (30)}{(10^4)\ (1/4)}$$

$= 0.0376 \rightarrow 4.75$ HVL's $\rightarrow 2.28$ mm Pb

3) Total secondary $2.28 + 0.48 = 2.76$ mm Pb

e. Ceiling

1) Secondary scatter, P = 0.01 R/wk, d_{sec} = 10' (3.05 m)

W = 10,000 mA - min/wk, T = 1/16, d_{sca} = 0.5 m, F = 400 cm^2

$$K = \frac{0.01}{(10^{-3})\ (10^4)\ (1/16)}\ (3.05)^2\ (0.5)^2\ \frac{(400)}{(400)}$$

$= 0.037 \rightarrow 1.1$ mm Pb

2) Secondary leakage, $I = 30$ mA, $d_{sec} = 7\ 1/2'$ (2.29 m)

$$B = \frac{(0.01)\ (2.29)^2\ (60)\ (30)}{(10^4)\ (1/16)}$$

$$= 0.0376 \rightarrow 4.75 \text{ HVL's} \rightarrow 2.28 \text{ mm Pb}$$

3) Total barrier $2.28 + 0.48 = 2.76$ mm Pb

3. Summary

Barrier	Total Lead Equivalent - mm	
North wall	3.3	(5/32")*
East wall, door, window	2.13	(3/32")*
South wall	2.35	(3/32")*
West wall	2.76	(1/8")*
Ceiling	2.76	(1/8")*

* Thickness of commercial sheet lead.

LECTURE NO. 14

TITLE:	Radiation Protection Survey
PURPOSE:	To present current recommendations and regulations upon which radiation surveys are based
TIME:	One hour
VISUAL AIDS:	Blackboard
HANDOUTS:	None
REFERENCES:	NBS Handbook 93 NCRP Report 33 NCRP Report 34 NCRP Report 35 OSBH Regulations

RADIATION PROTECTION SURVEY

I. Introduction

A radiation protection survey is an evaluation of the radiation levels in and around an installation. It customarily includes a physical survey of the arrangement and use of the equipment and measurements of the exposure rates under expected operating conditions.

All new installations, and existing installations not previously surveyed, are required to have a protection survey made by a person having the knowledge and training necessary to measure ionizing radiations and to advise regarding radiation protection.

II. Radiation Protection Regulations and Recommendations

A. X-ray protection is accomplished through the combined efforts of all interested parties.

1. Manufacturers of apparatus.
2. Designers and builders of x-ray installations.
3. Operators of the x-ray equipment.

B. To guide, advise, and provide checks on the effectiveness of these individuals, certain guide lines must be established.

C. The National Council on Radiation Protection and Measurements (NCRP) has been established to meet this need.

III. NCRP

A. Non-profit corporation chartered by Congress in 1964 to:

1. Collect, analyze, develop, and disseminate information and recommendations concerned with radiation protection;
2. Provide a means by which organizations may cooperate for effective utilization of their combined resources, and to stimulate the work of such organizations;

3. Develop basic concepts about radiation quantities, units and measurements, about the application of these concepts, and about radiation protection;
4. Cooperate with all authoritative groups or organizations concerned with radiation protection.

B. The Council is the successor to the National Committee on Radiation Protection and Measurements.

C. Scientific Committees of the Council.
1. Composed of experts having detailed knowledge and competence in a particular area.
2. Proposed recommendations are submitted to the full membership of the Council for consideration before being published.
3. Recommendations formerly published as NBS Handbooks. Present recommendations are published as NCRP Reports.

D. Recommendations of NCRP on medical radiation protection found in NCRP Report Nos. 33 and 34.

E. The recommendations of the NCRP form the basis for most medical x-ray protection regulations adopted by the Council of State Government and State Radiation Regulatory Agencies.

IV. <u>Terminology of Radiation Protection</u>

A. Terms having specific implications:
1. shall -- necessary to meet currently accepted standards of radiation protection.
2. should -- advisory recommendation to be applied when practicable.

B. Terms relating to equipment:
1. Filtration
   a. inherent
   b. added
   c. total

2. Kilovoltage
    a. kVp
    b. kVcp
3. Dead-man type switch
4. Interlock
5. Protective tube housing
    a. diagnostic type
    b. therapeutic type

C. Terms relating to shielding:
1. Controlled area
2. Uncontrolled area
3. Occupancy factor
4. Use factor
5. Workload
6. Protective barriers
    a. primary
    b. secondary
7. Radiation
    a. leakage
    b. scatter
    c. secondary
    d. stray
    e. useful beam

V. <u>General Recommendations on Surveys</u>

A. Protection Survey
1. New and existing installations
2. Beam restriction and collimation
3. Interlocks
4. Personnel monitoring evaluation
5. Exposure measurements
6. Tube housing leakage

B. Survey Report

1. To person in charge and to person requesting survey
2. Measured exposure levels
3. Recommended corrective measures
4. Recommend re-survey if necessary
5. Copies of report

C. Periodic Inspections

1. Physical inspection of equipment
2. Operating procedures
3. Workloads and occupancy
4. Correct hazards if found

VI. <u>Recommendations on Working Conditions</u>

A. Responsibilities of the user

B. Responsibilities of the operator

C. Responsibilities of the Radiation Protection Officer

D. Personnel monitoring

E. Health records

VII. <u>Recommendations for Specific Applications</u>

A. Medical Fluoroscopic

1. Equipment
2. Structural shielding
3. Operating procedures

B. Medical Radiographic (same as A.)

C. Mobile Diagnostic Equipment (same as A.)

D. Chest Photo Fluorographic (same as A.)

E. Dental Radiographic (same as A.)

F. Therapeutic up to 3 Mev (same as A.)

G. Therapeutic, 60 kV and below (same as A.)

GS-462 X-RAY MEASUREMENT

SECTION II

LABORATORY EXERCISES

LABORATORY NO. 1

TITLE: X-Ray Output Waveform

PURPOSE: To study x-ray output waveform as a function of kilovoltage, tube current and filtration.

TIME: Three hours

MATERIAL FOR EACH STUDENT GROUP:

One Teaching X-Ray Unit
One solid-state x-ray detector
One Heath Co. 3" d.c. oscilloscope
Two sheets linear graph paper, K & E 46-0703 or equivalent

LABORATORY NO. 1
X-RAY OUTPUT WAVEFORM

I. Introduction

The purpose of this laboratory exercise is to investigate the x-ray output waveform from a typical self-rectified x-ray machine, func- tion of kilovoltage, tube current and filtration.

The spectral distribution of the radiation output from an x-ray machine can be measured and/or calculated with reasonable accuracy. The measurement system of choice involves a "large" scintillation crystal and multichannel analizer system which will sample and present intensity as a function of energy. To calculate spectra requires a precise attenuation curve in aluminum or copper. Measurement systems are expensive and to calculate the spectra is time consuming unless computer facilities are available.

In this laboratory exercise we will investigate the x-ray output waveform from a typical x-ray machine using an inexpensive solid-state detector and inexpensive oscilloscope. It is important to understand that "x-ray output waveform" is not equivalent to "x-ray output spectrum" in that the solid-state detector indicates intensity as a function of time during the electrical cycle rather than intensity as a function of energy (kilovoltage). A solid-state amplifier between the detector and readout system increases the detector signal so as to provide adequate signal to the readout system. The readout system is a 3" d.c. oscilloscope. Using this system the relative x-ray output waveform can be determined at minimum expense.

II. Equipment

A. Teaching X-Ray Unit

B. Solid State X-Ray Detector

C. Heath Co. 3" d.c. oscilloscope

D. Linear graph paper

III. Procedure

A. Connect the two 9 volt batteries to the detector amplifier.

B. Place the detector on the bottom of the Teaching X-Ray Unit enclosure in the center of the enclosure.

1. Route the detector to amplifier cable through the groove between the left-hand door and the cabinet. Close the enclosure doors.
2. Connect the banana plug terminals on the output cable from the amplifier to the vertical amplifier 'scope terminals, red to red, black to black (ground).
3. Position the amplifier and any excess cable such that you have ample working room on the Teaching X-Ray Unit cart.
4. Connect a wire between the oscilloscope vertical amplifier ground terminal and the x-ray control metal cabinet.
5. Turn on the oscilloscope and let it warm up for at least 2 minutes. Set the oscilloscope controls as follows:
   a. Horizontal amplifier DCX 100
   b. Vertical amplifier DCX 1
   c. Sweep frequency 5
   d. Make any fine adjustments so as to get an undistorted horizontal trace across the scope scale with the trace located at the bottom horizontal scale line. This will take some trial and error attempts. If you have difficulty enlist the aid of the instructor, since setting up an oscilloscope requires experience.

C. In each of the following sections, set up and operate the x-ray machine at the first data point, which will be the maximum exposure rate condition. Make repeated exposures until you have adjusted the oscilloscope settings such that the base line is at the bottom oscilloscope scale, the trace peak is at the top oscilloscope scale and that one complete waveform occupies the horizontal oscilloscope scale. Once the horizontal and vertical scale settings have been established for the first data point, do not change these settings. This also takes experience with oscilloscopes so enlist the aid of your instructor if you have problems.

D. Effect of kilovoltage on x-ray output waveform.

1. Set up the x-ray machine as shown below.
2. On linear graph paper copy, as accurately as possible, the x-ray output waveform as displayed on the oscilloscope.

kVp	mA	Added Filter
100	3.0	0
90	"	"
80	"	"
70	"	"
60	"	"
50	"	"

E. Effect of tube current on x-ray output waveform.

1. Set up the x-ray machine as shown below.
2. On linear graph paper copy, as accurately as possible, the x-ray output waveform as displayed on the oscilloscope.

kVp	mA	Added Filter
70	5	0
"	3	"
"	1	"

F. Effect of filtration on x-ray output waveform.

1. Set up the x-ray machine as shown below.
2. On linear graph paper copy, as accurately as possible, the x-ray output waveform as displayed on the oscilloscope.

kVp	mA	Added Filter
70	3.0	0
"	"	1.0mm Al
"	"	2.0mm Al
"	"	3.0mm Al

IV. Questions

1. Calculate the area under the waveforms in Parts III,D, E, and F. Does this represent relative exposure rate in each case?
2. For each experimental condition (Part III D, III E, and III F) explain the change in waveform.

Laboratory No. 1

TYPICAL DATA

IV. 1. Area under x-ray output waveforms

kVp	Relative Area
100	115
90	100
80	90
70	75
60	55
50	50

mA	Relative Area
5	115
3	75
1	30

Added Filter

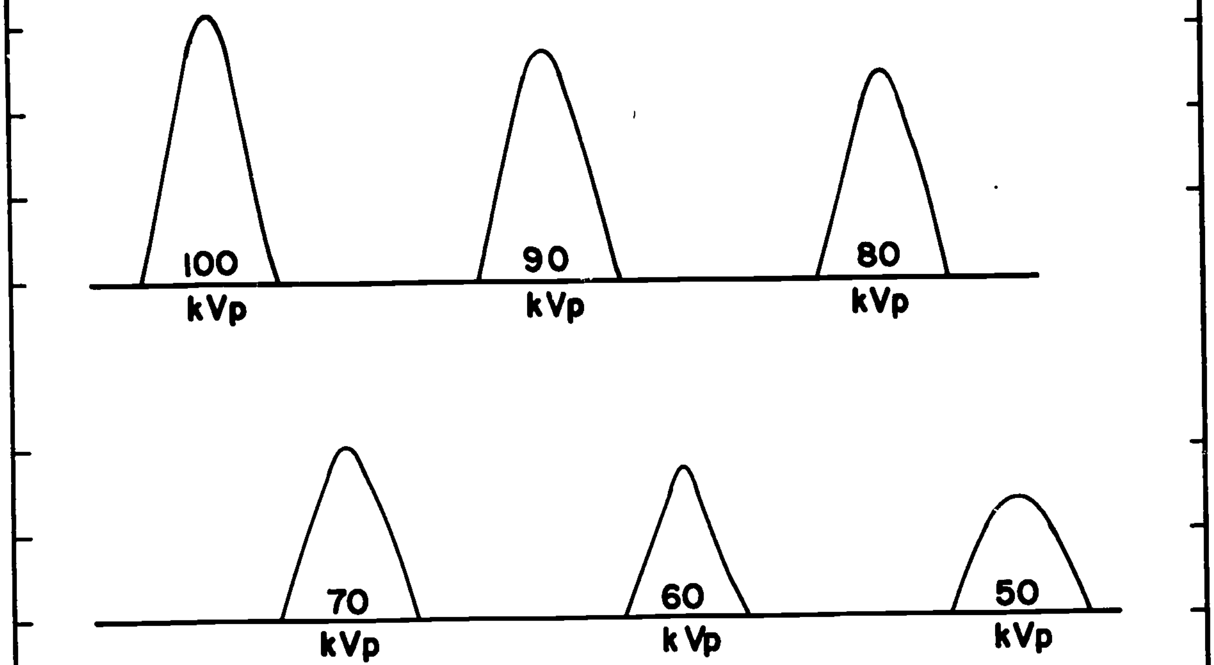
mmAl	Relative Area
0	115
1	65
2	40
3	25

Within experimental error the area under the waveforms does represent relative exposure rate in that the relative areas follow exposure rates determined in GS-461, Laboratory No. 4. (See 2 Following)

2. In all cases, the peak of the waveform decreased with decreasing exposure rate. As kVp is decreased, exposure rate is decreased resulting in a reduced "peak" exposure rate and reduced total area under the waveform. Over the energy range, exposure rate is a linear function of kilovoltage and the area under the waveforms is essentially a linear function of kilovoltage. The same is true of exposure rate and waveform area as a function of tube current. Both exposure rate and waveform area are an exponential function of added filtration.

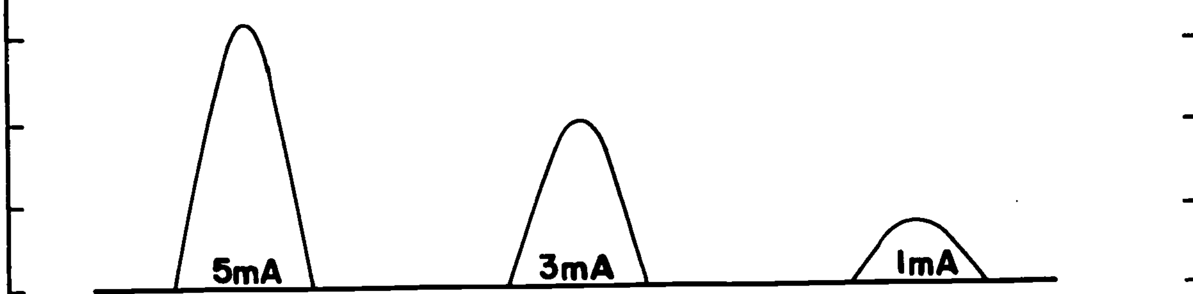
Laboratory No I, Section III, Part D2

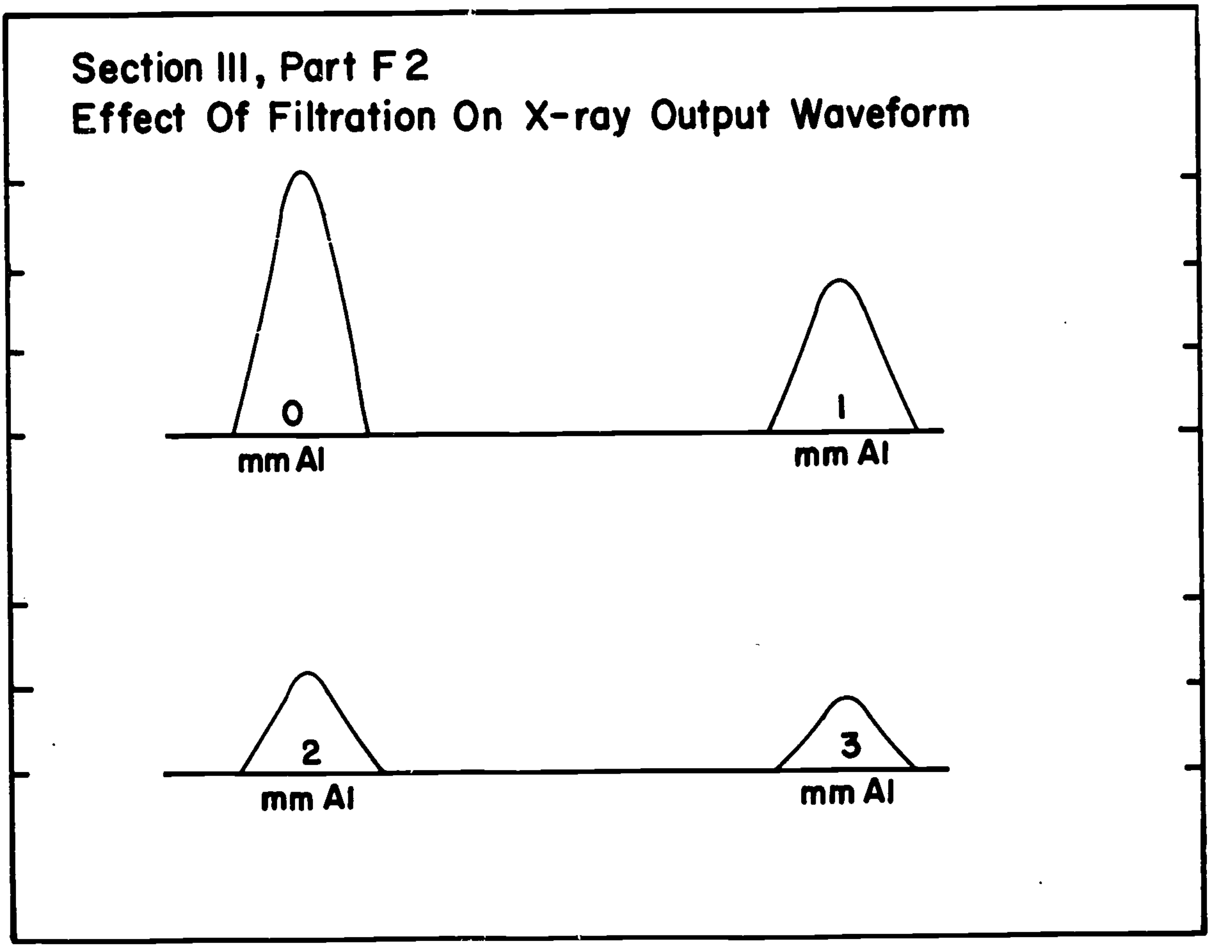
Effect Of Kilovoltage On X-ray Output Waveform



Section III, Part E 2

Effect Of Tube Current On X-ray Output Waveform




Section III, Part F2
Effect Of Filtration On X-ray Output Waveform
0
mm Al
1
mm Al
2
mm Al
3
mm Al

LABORATORY No. 2

TITLE: Factors Affecting Patient and Operator Exposure

PURPOSE: To study the effects of atomic number, kVp, filtration and mA upon scattered radiation and patient and operator exposure.

TIME: Three hours

MATERIALS FOR EACH STUDENT GROUP:

One GE Maximar 100 X-Ray Machine
One 10 x 30 cm cone
One 15 x 30 cm cone
One 20 x 30 cm cone
One 3 mm Al filter
One 1 mm Al filter
Two Victoreen Model 555 Radocon II
Two Victoreen Model 555-0.1 MA probes
One 8" x 10" x 0.020" copper sheet
One 8" x 10" x 0.125" aluminum sheet
One 8' x 10' x 0.750' wood sheet
One wood dowel stand
One 16 oz. water-filled plastic bottle
One chest phantom
Three sheets linear graph paper, K & E 46-0703 or equivalent
One ships curve, K & E 1685-48 or equivalent
One sheet polargraph paper Dietzgen 340-RP or equivalent

REFERENCES: Attix, Roesch, Tochilin
Radiation Dosimetry

Evans
The Atomic Nucleus

Hine and Brownell
Radiation Dosimetry

Johns
The Physics of Radiology

Laboratory No. 2

FACTORS AFFECTING PATIENT AND OPERATOR EXPOSURE

I. INTRODUCTION

The purpose of this laboratory is to study the effects of atomic number, kVp, filtration, and mA upon scatter radiation and patient and operator exposure.

II. EQUIPMENT

A. General Electric Maximar 100 X-Ray Machine

B. Cones

1. 10 x 30 cm
2. 15 x 30 cm
3. 20 x 30 cm

C. Filters

1. 1 mm Al
2. 3 mm Al

D. Victoreen Radocon II, model 555 (two required)

E. Victoreen probes, model 555-0.1 MA (two required)

F. Materials

1. 8" x 10" x 0.04" copper sheet
2. 8" x 10" x 0.04" aluminum sheet
3. 8" x 10" x 0.750" wood sheet

4. Wood dowel stand

5. H_2O filled plastic bottle

6. Chest Phantom

III. X-RAY SCATTER MEASUREMENTS

A. Effect of X-ray Energy Upon Compton Scatter

1. Arrange equipment as shown in Figure 1 with no attenuator in the primary beam.

2. Operate the x-ray machine at 3 mA and 3 mm of Al added filtration and measure the exposure rates at Positions A and B for 50 through 90 kVp in steps of 10 kV.

3. Place the aluminum attenuator in the beam and repeat Step 2.

4. Calculate the net scatter exposure rate at Position B.

5. Normalize the net scatter at B to a unit rate of interaction.

6. Plot the normalized net scatter factor vs kVp.

B. Effect of Atomic Number Upon Compton Scatter

1. Arrange equipment as shown in Figure 1.

2. Operate the x-ray machine at 90 kVp and 3 mA with 3 mm of Al added filtration. Measure the exposure rates at Positions A and B.

3. Place the aluminum attenuator in the beam and repeat Step 2.

4. Repeat Step 3 with copper attenuator.

5. Repeat Step 3 with the wood attenuator.

6. Claculate normalized net scatter factors for each material as in Section III-A.

7. Plot scatter factors vs Atomic Number

C. Distribution of Scattered X Rays

1. Arrange equipment as shown in Figure 2.

2. Operate the X-ray machine at 90 kVp and 3 mA with 3 mm of Al added filtration.

3. Measure the exposure rate at Positions A through E with and without the cylindrical scattering object in the primary beam.

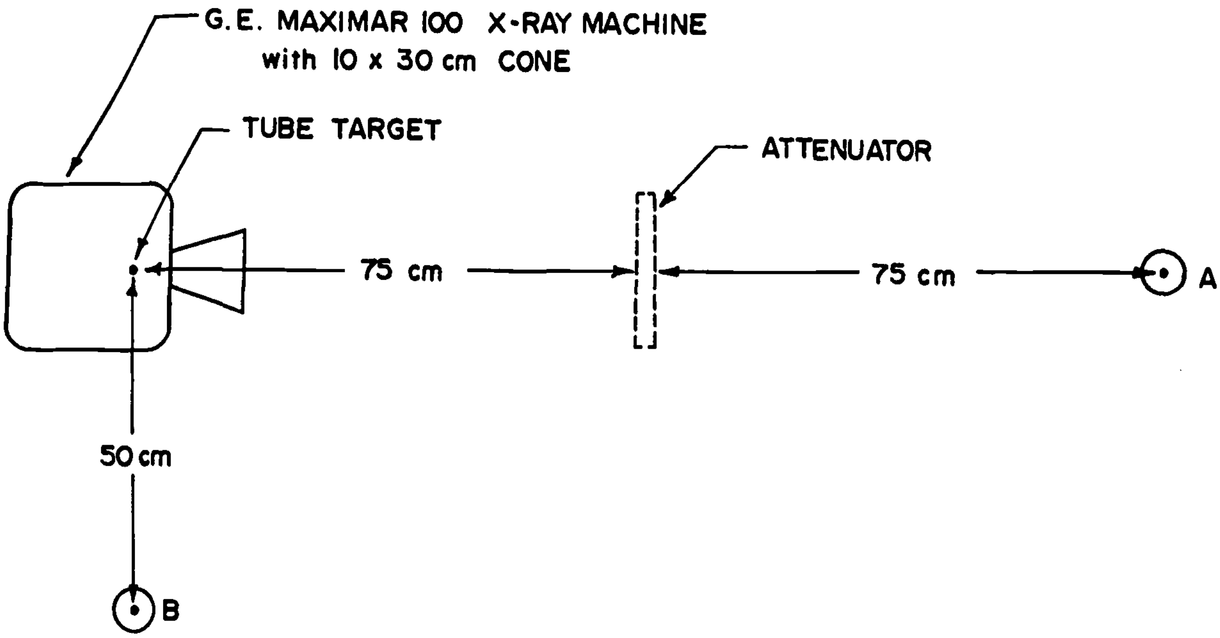
4. Calculate the net exposure rate at each position.

5. Plot the exposure rate vs angle of scatter on polar coordinate graph paper. Assume symmetry with respect to the beam axis and draw curve on both sides of the primary beam.

IV. EFFECT OF X-RAY MACHINE FACTORS UPON PATIENT AND OPERATOR EXPOSURE

A. kVp and Filtration

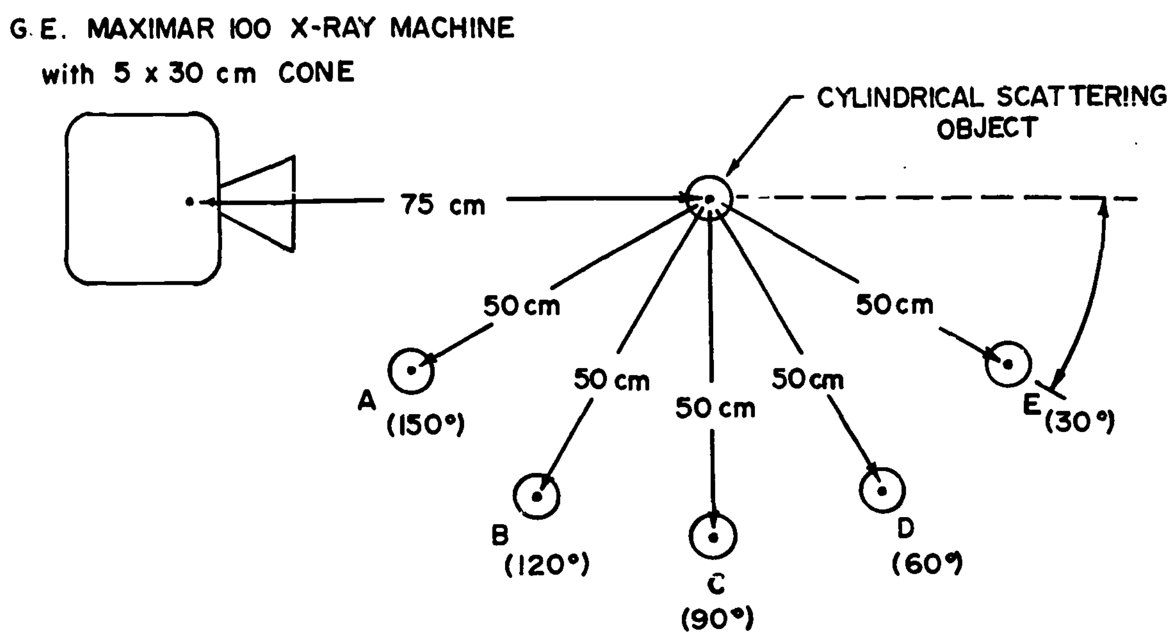
1. Arrange equipment as shown in Figure 3.



CHAMBER A and B – MODEL 555 – 0.1 mA PROBE
CONNECTED TO VICTOREEN RADOCON II

FIGURE 1

2. Operate the x-ray machine at 60 kVp and 5 mA with 3 mm of Al added filtration and the 10 x 30 cm cone in place. Measure the exposure rate at Position B.



CHAMBER A-E MODEL 555 - 0.1 mA PROBE

FIGURE 2

3. Operate the x-ray machine at 90 kVp with 3 mm of Al added filtration and determine the mA setting which results in the same exposure rate at B as found in Step 2.

4. Repeat Step 3 except use 60 kVp and 1 mm of Al added filtration.

5. Repeat Step 3 except use 90 kVp and 1 mm of Al added filtration.

6. Using the same settings as in Step 5, measure and record the exposure rate at Position A and C.

7. Repeat Step 6 using the settings of Step 4.

8. Repeat Step 6 using the settings of Step 3.

9. Repeat Step 6 using the settings of Step 2.

10. Calculate relative entrance exposure and scatter factors using the 90 kVp, 3 mm Al filtration technique as unity in each case. Report data as follows:

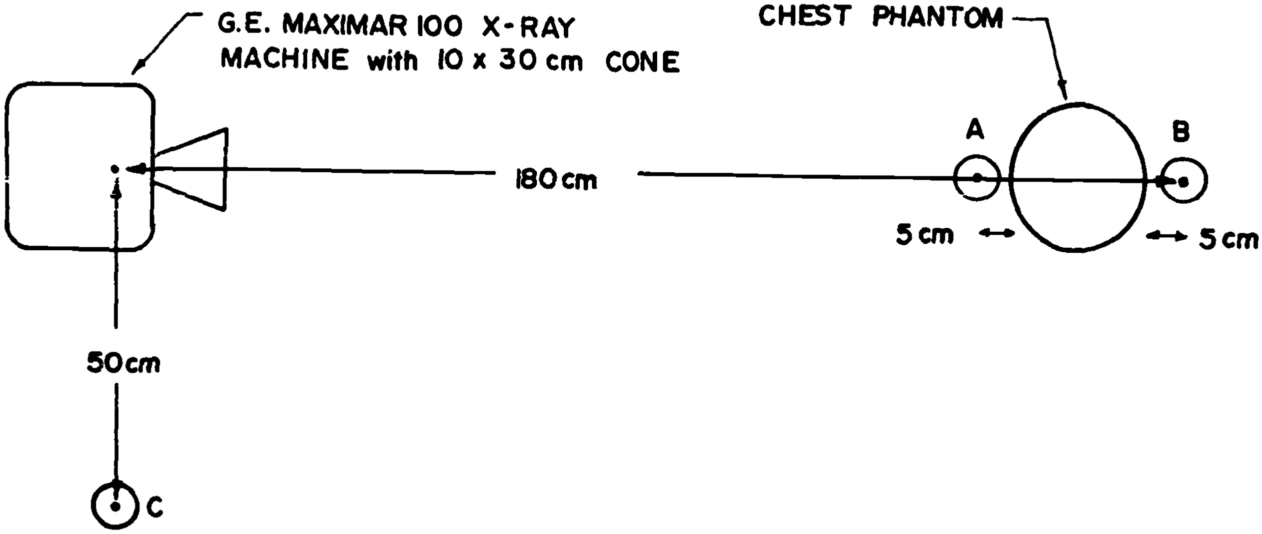
kVp	Added Al Filtration	mA	Exit Exposure Rate	Relative Entrance Exposure	Relative Scatter Factor
90	3 mm	5	______	1.0	1.0
60	3 mm	__	______	______	______
90	1 mm	__	______	______	______
60	1 mm	__	______	______	______

B. Collimation

1. Arrange equipment as shown in Figure 3.

2. Operate the x-ray machine at 90 kVp and 3 mA with 3 mm of Al added filtration with the 10 x 30 cm cone in place. Measure the scatter at Position C.

3. Replace the cone with the 15 x 30 cm cone and repeat Step 2.



CHAMBER A, B and C – MODEL 555 - 0.1 mA PROBE
CONNECTED TO VICTOREEN RADOCON II

FIGURE 3

4. Replace the cone with the 20 x 30 cm cone and repeat Step 2.

5. Calculate the beam diameter at Position B for each cone used.

6. Plot beam diameter vs scatter reading. Assume a value for scatter at zero beam diameter and extrapolate curve through this point.

Laboratory No. 2

TYPICAL DATA

Part III, A. Effect of x-ray energy on scatter

Attenuator	kVp	mA	R/min "A"-pri	mR/h "B"-sec	mR/h Net Scatter	Normalized Scatter
None	50	3	.098	6.0	--	--
"	60	"	.166	10.5	--	--
"	70	"	.249	16.3	--	--
"	80	"	.322	22.3	--	--
"	90	"	.425	30.0	--	--
Alumimum	50	3	.028	10.8	4.8	68.2
"	60	"	.059	22.0	11.5	107.6
"	70	"	.096	33.0	16.7	109.2
"	80	"	.141	46.0	23.7	131
"	90	"	.195	63.0	33.0	141

Part III, B. Effect of atomic number on scatter

Attenuator	kVp	mA	R/min "A"-pri	mR/h "B"-sec	mR/h Net Scatter	Normalized Scatter
Aluminum	90	3	.195	63	33	141
Copper	"	"	.056	61	31	84
Wood	"	"	.325	147	117	1170

Part III, C. Distribution of scatter

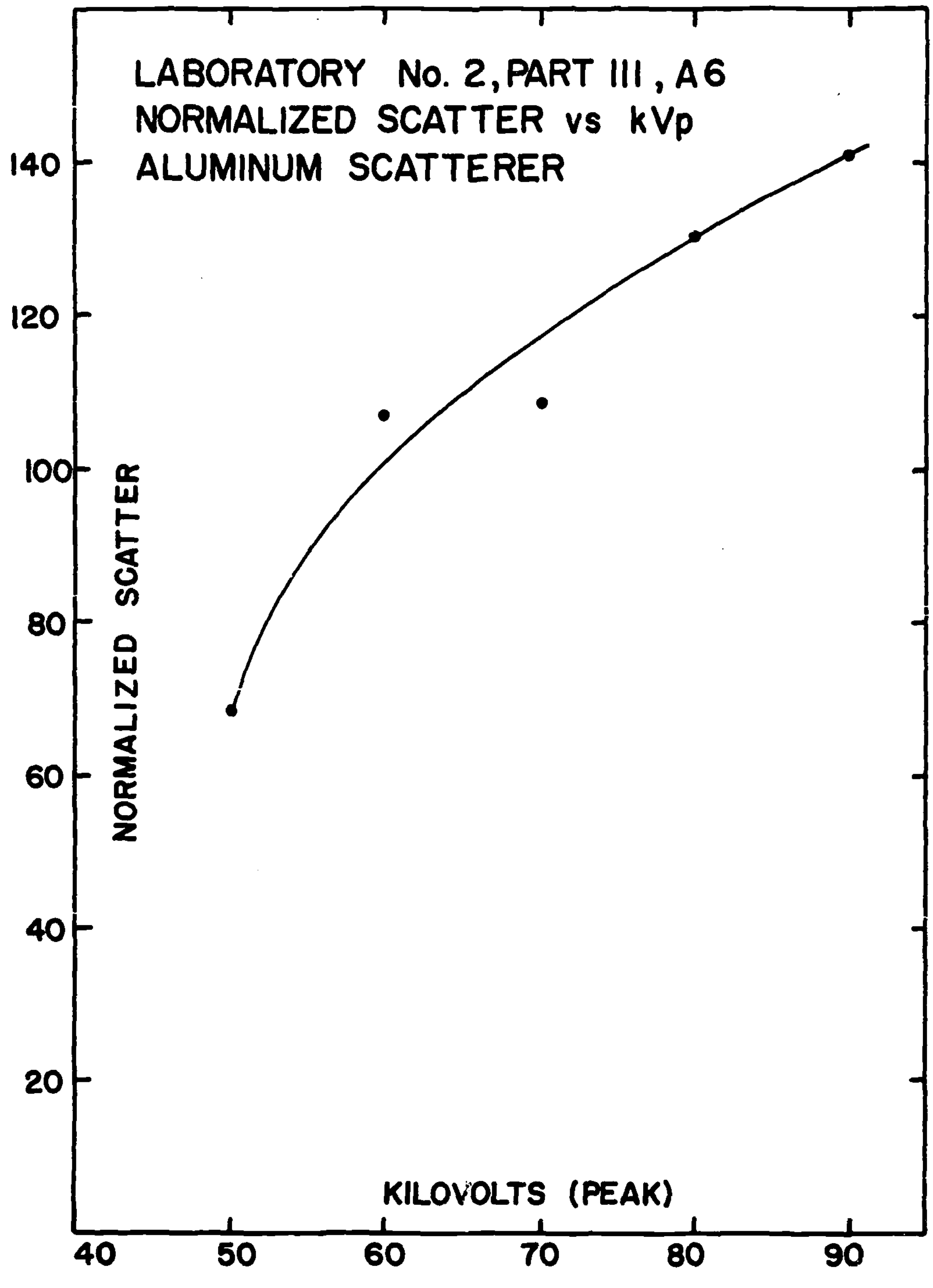
Angle	Scatter	Sec-mR/h	Net Scatter-mR/h
150°	In	238	134
"	Out	104	
120°	In	143	108
"	Out	35	
90°	In	117	92
"	Out	25	
60°	In	156	130
"	Out	26	
30°	In	236	191
"	Out	45	

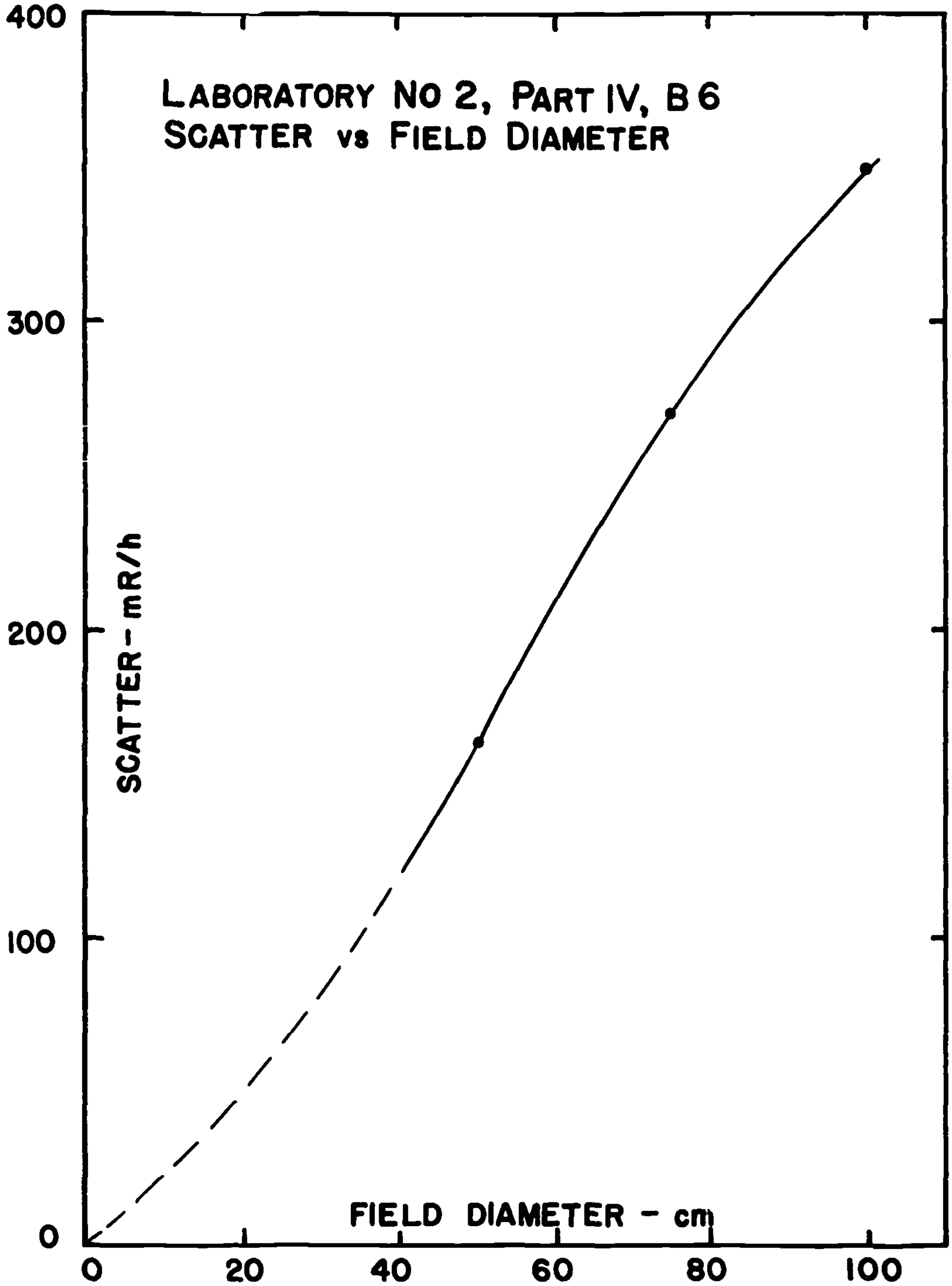
Part IV, A. Effect of kVp and filtration on patient and operator exposure

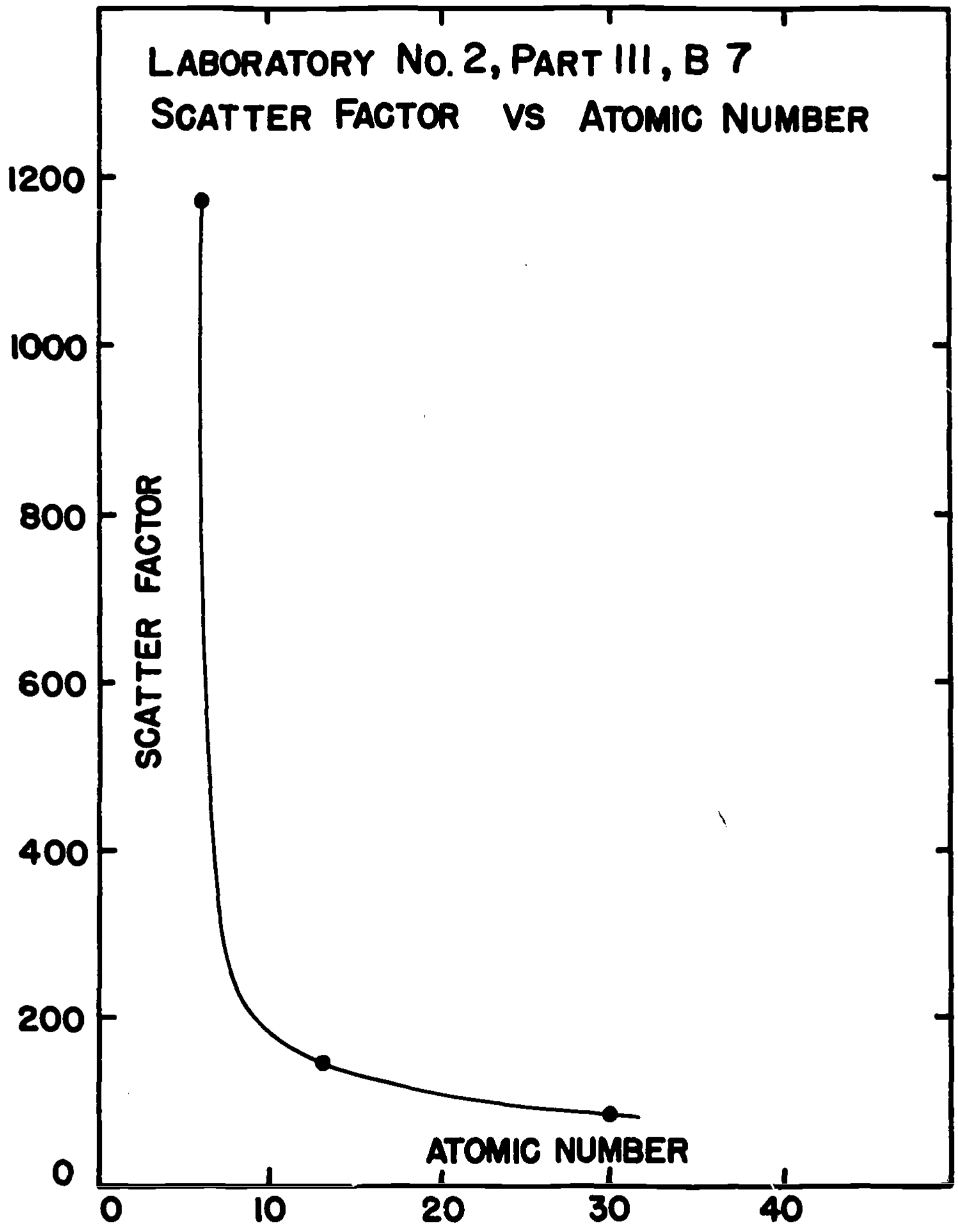
kVp	mA	Filter-mm	R/min "B"-exit	R/min "A"-entrance	mR/h "C"-secondary
60	5	3 Al	0.0145	.41	73
90	.85	3 Al	"	.25	54
60	2.17	1 Al	"	.79	96
90	0.60	1 Al	"	.45	68

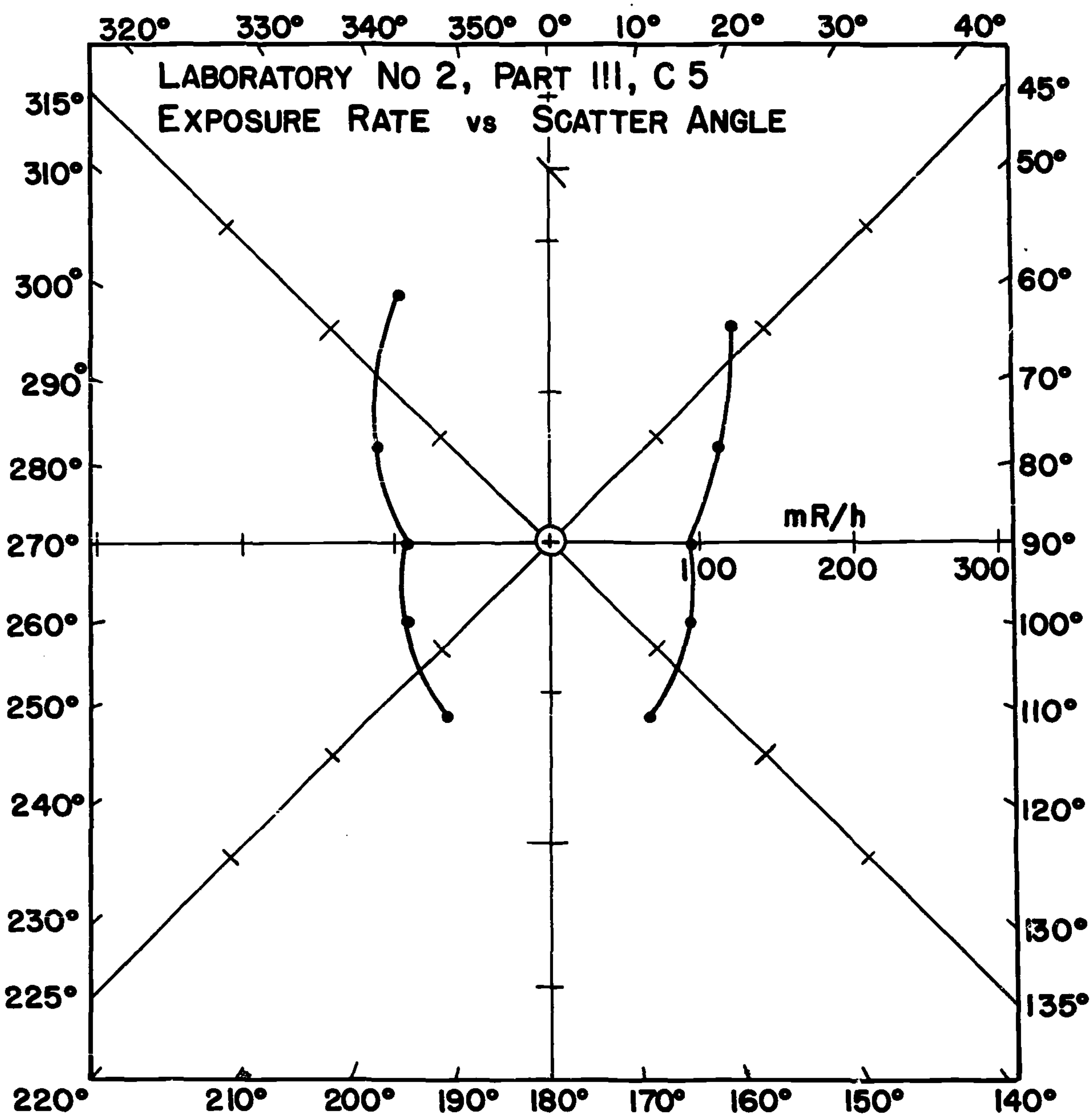
Part IV, B. Effect of field size on operator exposure

Cone-cm	Dia. at Phantom-cm	mR/h
0	0	0
10 x 30	50	163
15 x 30	75	270
20 x 30	100	350


LABORATORY No. 2, PART III, A6
NORMALIZED SCATTER vs kVp
ALUMINUM SCATTERER
NORMALIZED SCATTER
KILOVOLTS (PEAK)
140
120
100
80
60
40
20
40
50
60
70
80
90


LABORATORY NO 2, PART IV, B 6
SCATTER vs FIELD DIAMETER
400
300
200
100
0
SCATTER - mR/h
FIELD DIAMETER - cm
0
20
40
60
80
100


LABORATORY NO. 2, PART III, B 7
SCATTER FACTOR VS ATOMIC NUMBER
SCATTER FACTOR
ATOMIC NUMBER
1200
1000
800
600
400
200
0
0
10
20
30
40


LABORATORY NO 2, PART III, C 5
EXPOSURE RATE vs SCATTER ANGLE
320° 330° 340° 350° 0° 10° 20° 30° 40°
315° 310° 300° 290° 280° 270° 260° 250° 240° 230° 225° 220°
45° 50° 60° 70° 80° 90° 100° 110° 120° 130° 135° 140°
210° 200° 190° 180° 170° 160° 150°
mR/h
100 200 300

LABORATORY NO. 3

TITLE: Determination of X-ray Field Distribution

PURPOSE: To study the x-ray field distribution from an x-ray machine.

TIME: One and one-half hours

MATERIALS FOR EACH STUDENT GROUP:

One Teaching X-Ray Unit
One Condenser R-meter with 25-R medium energy chamber
One chamber holder
Two sheets linear graph paper, K & E 46-0703 or equivalent
One ships curve, K & E 1685-48 or equivalent

REFERENCES:

Atlee, Z. J. and E. D. Trout
"A" study of Roentgen-Ray Distribution at 60-140 kVp"
Radiology, 40 (4), pp. 375-385, April 1943

Laboratory No. 3

DETERMINATION OF X-RAY FIELD DISTRIBUTION

I. INTRODUCTION

The purpose of this laboratory is to study the x-ray field distribution from an x-ray machine.

II. EQUIPMENT

A. Teaching X-Ray Unit

B. Condenser R-meter with 25-R medium energy chamber

C. Chamber holder

III. PROCEDURE

A. Determination of x-ray field distribution

1. Under the following conditions using an open field (not diaphragmed) measure the exposure at the center of the field using an exposure time of 45 seconds. Then at 1 inch intervals measure the exposure along the tube axis. Convert the exposures to percentages with that on the beam axis (center of the field) as 100%.

kVp	mA	SCD	Filter	Position	R	%
70	3	35 cm	Inherent	Center	______	100
"	"	"	"	1 inch right	______	______
"	"	"	"	2 inches right	______	______
"	"	"	"	3 inches right	______	______
"	"	"	"	4 inches right	______	______
"	"	"	"	1 inch left	______	______
"	"	"	"	2 inches left	______	______
"	"	"	"	3 inches left	______	______
"	"	"	"	4 inches left	______	______

2. Repeat, measuring the exposure at 1 inch intervals perpendicular to the tube axis

kVp	mA	SCD	Filter	Position	R	%
70	3	35 cm	Inherent	Center	______	100
"	"	"	"	1 inch back	______	______
"	"	"	"	2 inches back	______	______
"	"	"	"	3 inches back	______	______
"	"	"	"	4 inches back	______	______
"	"	"	"	1 inch front	______	______
"	"	"	"	2 inches front	______	______
"	"	"	"	3 inches front	______	______
"	"	"	"	4 inches front	______	______

3. On separate sheets of linear graph paper plot exposure percentage vs distance from field center for parts III, A, 1 and 2.

IV. QUESTIONS

A. What is the "heel" effect; how does it alter the x-ray field distribution?

B. Given a SCD of 50 cm and a field diameter of 36 cm, evaluate the reduction in intensity at the edges of the field due only to the inverse square law.

Laboratory 3

TYPICAL DATA

Part III, A. X-ray field distribution

1. Parallel to x-ray tube axis

Position	Percent
Axis	100
1 inch right	82.5
2 inches right	47.5
3 inches right	5
4 inches right	3
1 inch left	107.0
2 inches left	107.5
3 inches left	104.2
4 inches left	2.5

2. Perpendicular to x-ray tube axis

Position	Percent
Axis	100
1 inch back	100
2 inches back	100
3 inches back	93.5
4 inches back	1.5
1 inch front	100
2 inches front	99
3 inches front	94
4 inches front	2

Part IV. Answers to questions

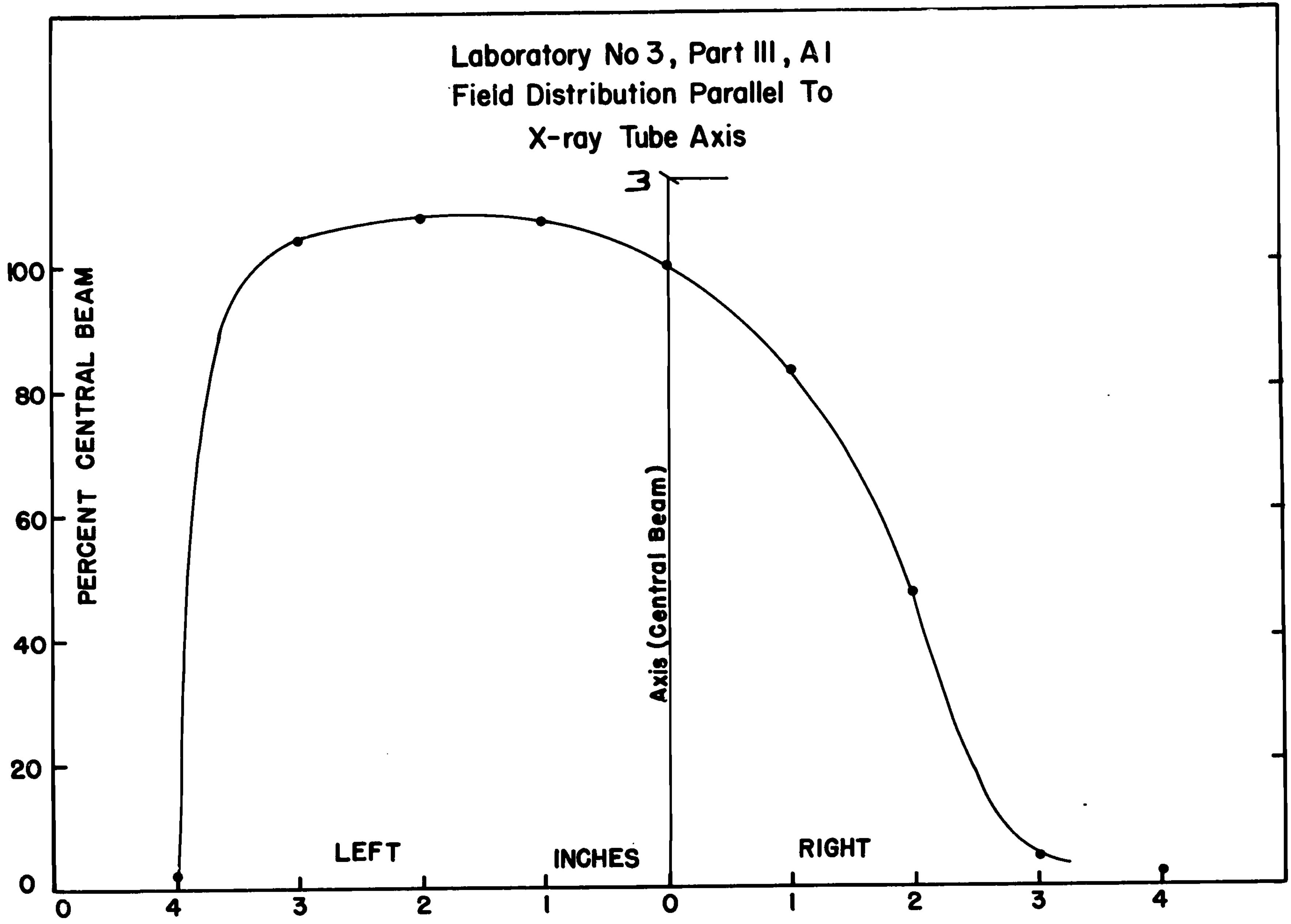
A. The "heel" effect is the name given to the effect produced by attenuation of x-rays within the target. The "heel" effect occurs because not all x rays are produced at the outermost surface of the target. The electrons penetrate the surface and x rays are produced at a depth within the target. The x rays produced within the target are filtered by the tungsten of the target resulting in a loss in intensity. The amount of tungsten that must be penetrated increases toward the "heel" of the target (the anode end of the x-ray tube) due to target angle.

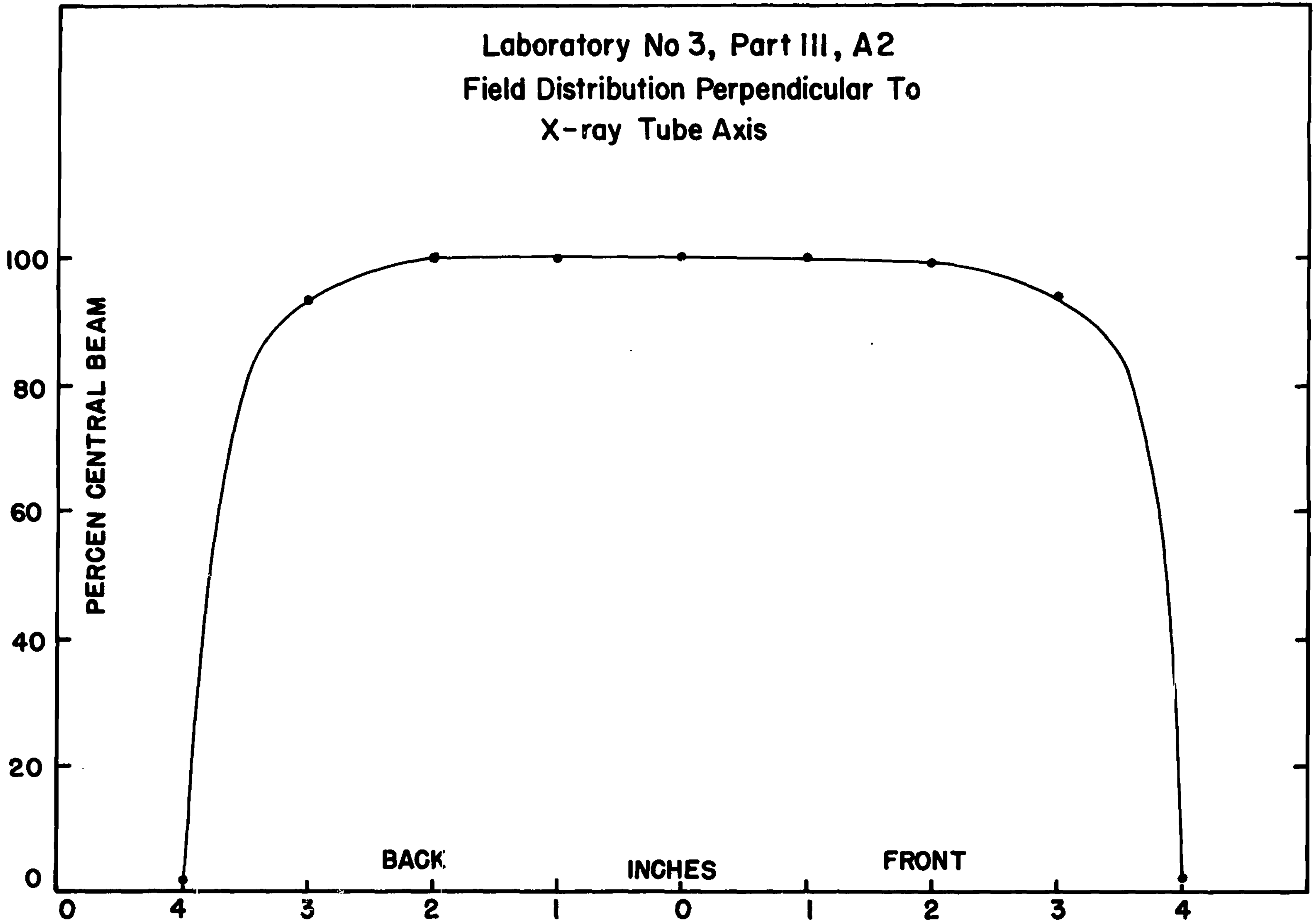
B. $$X^2 = (SCD)^2 + \left(\frac{\text{Field Diameter}}{2}\right)^2$$

$$X^2 = (50)^2 + \left(\frac{36}{2}\right)^2 = 2824$$

$$\frac{SCD}{X^2} = \frac{(50)^2}{2824} = 0.885$$

$\therefore$ Intensity at field edge is reduced 11.5%


Laboratory No 3, Part III, A I
Field Distribution Parallel To
X-ray Tube Axis
3
PERCENT CENTRAL BEAM
100
80
60
40
20
0
Axis (Central Beam)
LEFT
INCHES
RIGHT
0
4
3
2
1
0
1
2
3
4


Laboratory No 3, Part III, A2
Field Distribution Perpendicular To
X-ray Tube Axis
PERCEN CENTRAL BEAM
100
80
60
40
20
0
BACK
INCHES
FRONT
0
4
3
2
1
0
1
2
3
4

LABORATORY No. 4

TITLE: Determination of Half-Value Layer

PURPOSE: To determine the first half-value layer, second half-value layer and the homogeneity coefficient for both "broad beam" and "unique" conditions of geometry.

TIME: One and one-half hours

EQUIPMENT FOR EACH STUDENT GROUP:

One Teaching X-Ray Unit
One Victoreen R-meter with 25-R chamber
One chamber holder
One 0.25 mm aluminum filter
One 0.5 mm aluminum filter
Three 1.0 mm aluminum filters
One 1.0 cm diameter lead diaphragm
One 4.0 cm diameter lead diaphragm

REFERENCES: Trout, E. D., J. P. Kelley and A. C. Lucas, Determination of Half-Value Layer, American Journal of Roentgenology, Radium Therapy and Nuclear Medicine, Vol. 84, No. 4, 729-740, October 1960.

Trout, E. D., J. P. Kelley and A. C. Lucas, The Second Half-Value Layer and the Homogeneity Coefficient, American Journal of Roentenology, Radium Therapy and Nuclear Medicine, Vol. 87, No. 3, 574-584, March 1962.

MATERIALS: Three sheets of linear graph paper, K & E 46-0703 or equivalent
Two sheets of 2-cycle semi-log paper, K & E 46-5253 or equivalent
One straight edge
One ships curve, K & E 1685-48 or equivalent

LABORATORY No. 4

OBJECT

To make exposure rate measurements through increasing thicknesses of aluminum at two kilovoltages and with two field sizes, to plot these data as absorption curves, from the curves determine the first and second half-value layers and the homogeneity factor, and from these data determine the "unique" first and second half-value layers and homogeneity factor.

PROCEDURE

Part I - Determination of Half-value layer, 50 kVp.

A. Determine the exposure rate in R/minute with no added filter, 1/4 mmAl, 1/2 mmAl, 1 mmAl, and 2 mmAl added filter operating the x-ray unit at 50 kVp, 3.0 mA with a 25 cm SCD and using the 4 cm diameter lead diaphragm.

B. On a sheet of semi-log paper, plot exposure rate vs added filtration.

C. From the absorption curve determine the first half-value layer, the second half-value layer and the homogeneity factor.

D. Repeat Part I A using a 1.0 cm diameter diaphragm.

E. On a second sheet of semi-log paper plot the exposure rate vs added filtration.

F. From the absorption curve determine the first half-value layer, second half-value layer and the homogeneity factor.

Part II - Determination of half-value layer, 100 kVp.

A. Determine the exposure rate in R/minute with no added filter, 1/4 mmAl, 1/2 mmAl, 1 mmAl, 2 mmAl, 3 mmAl, and 3 1/2 mmAl added filter operating the x-ray unit at 100 kVp, 3.0 mA with a 25 cm SCD and using the 1 cm diameter lead diaphragm.

B. On the same sheet of semi-log paper used in Part I, E, plot exposure rate vs added filtration.

C. From the absorption curve, determine the first half-value layer, the second half-value layer and the homogeneity factor.

D. Repeat Part II, A using the 4.0 cm diameter diaphragm.

E. On the same sheet of semi-log paper used in Part I, B, plot exposure rate vs added filter.

F. From the absorption curve, determine the first half-value layer, second half-value layer and the homogeneity factor.

Part III - Determination of "unique" 1 HVL, 2 HVL and homogeneity factor.

A. On a sheet of cross-section paper, plot the first half-value layer vs field diameter for Part I, C and Part I, F and extrapolate to zero field diameter. The half-value layer at zero field is the "unique" half-value layer. Repeat for the second half-value layer. Determine the "unique" homogeneity factor.

B. On a second sheet of cross-section paper plot the first half-value layer vs field diameter for Part II, C and Part II, F and extrapolate to zero field diameter. Repeat for the second half-value layer. Determine the "unique" homogeneity factor.

Part IV - Questions

A. Define first and second half-value layer and homogeneity factor.

B. Discuss the variation of first and second half-value layer with field size at the filter.

C. Which half-value layer, first or second, is greater for a given x-ray beam and why?

D. Explain why the homogeneity factor is never greater than unity.

E. Given the following data and your data on "unique" first half-value layers (Part III), determine the effective energy of your 50 kVp and 100 kVp beams. Assume the density of aluminum to be 2.70 gm/cm^3.

Effective Energy and Mass Attenuation Coefficient

keV	μ / ρ - cm^2 / gm
10	26.2
15	7.9
20	3.37
30	1.11
40	0.543
50	0.353
60	0.268
80	0.197
100	0.169

Name____________________

Date____________________

Unit____________________

Temperature________________

Pressure__________________

Correction factor____________

Teaching X-Ray Unit

Laboratory No. 4 - Determination of half-value layer.

Part I, Section A. Absorption in aluminum: 50 kVp, 3 mA, 25 cm SCD, 4 cm diameter diaphragm.

Added Filter	Exposure Time	Uncorrected Exposure	Corrected Exposure	Exposure Rate
None	30 sec	______R	______R	______R/m
1/4 mm Al	60 sec	______R	______R	______R/m
1/2 mm Al	60 sec	______R	______R	______R/m
1 mm Al	90 sec	______R	______R	______R/m
2 mm Al	150 sec	______R	______R	______R/m

Part I, Section C. First half-value layer, second half-value layer and homogeneity factor: 50 kVp, 4 cm diameter diaphragm.

1 HVL-mm Al	2 HVL-mm Al	Homogeneity Factor
______	______	______

Part I, Section D. Absorption in aluminum: 50 kVp, 3 mA, 25 cm SCD, 1 cm diameter diaphragm.

Added Filter	Exposure Time	Uncorrected Exposure	Corrected Exposure	Exposure Rate
None	30 sec	______R	______R	______R/m
1/4 mm Al	60 sec	______R	______R	______R/m
1/2 mm Al	60 sec	______R	______R	______R/m
1 mm Al	90 sec	______R	______R	______R/m
2 mm Al	150 sec	______R	______R	______R/m

Part I, Section F. First half-value layer, second half-value layer and homogeneity factor: 50 kVp, 1 cm diameter diaphragm.

1 HVL-mm Al	2 HVL-mm Al	Homogeneity Factor
________	________	____________

Part II, Section A. Absorption in aluminum: 100 kVp, 3mA, 25 cm SCD, 1 cm diameter diaphragm.

Added Filter	Exposure Time	Uncorrected Exposure	Corrected Exposure	Exposure Rate
None	15 sec	________R	________R	________R/m
1/4 mm Al	15 sec	________R	________R	________R/m
1/2 mm Al	20 sec	________R	________R	________R/m
1 mm Al	30 sec	________R	________R	________R/m
2 mm Al	30 sec	________R	________R	________R/m
3 mm Al	40 sec	________R	________R	________R/m
3 1/2 mm Al	50 sec	________R	________R	________R/m

Part II, Section C. First half-value layer, second half-value layer and homogeneity factor: 100 kVp, 1 cm diameter diaphragm.

1 HVL-mm Al	2 HVL-mm Al	Homogeneity Factor
________	________	____________

Part II, Section D. Absorption in aluminum: 100 kVp, 3mA, 25 cm SCD, 4 cm diameter diaphragm.

Added Filter	Exposure Time	Uncorrected Exposure	Corrected Exposure	Exposure Rate
None	15 sec	________R	________R	________R/m
1/4 mm Al	15 sec	________R	________R	________R/m
1/2 mm Al	20 sec	________R	________R	________R/m
1 mm Al	30 sec	________R	________R	________R/m
2 mm Al	30 sec	________R	________R	________R/m
3 mm Al	40 sec	________R	________R	________R/m
3 1/2 mm Al	50 sec	________R	________R	________R/m

Part II, Section F. First half-value layer, second half-value layer and homogeneity factor: 100 kVp, 4 cm diameter diaphragm.

1 HVL-mm Al	2 HVL-mm Al	Homogeneity Factor
________	________	____________

Part III, Section A. "Unique" first half-value layer, second half-value layer and homogeneity factor: 50 kVp.

"Unique" 1 HVL-mm Al	"Unique" 2 HVL-mm Al	"Unique" Homogeneity Factor
________	________	____________

Part III, Section B. "Unique" first half-value layer, second half-value layer and homogeneity factor: 100 kVp.

"Unique" 1 HVL-mm Al	"Unique" 2 HVL-mm Al	"Unique" Homogeneity Factor
________	________	____________

Laboratory No. 4

TYPICAL DATA

Section I.A.

50 kVp, 4 cm field Added Filter mm Al	R/min
0	25.8
1/4	16.2
1/2	12.9
1	8.7
2	4.9

II.D.

100 kVp, 4 cm field Added Filter mm Al	R/min
0	62.8
1/4	46.8
1/2	41.4
1	32.8
2	23.0
3	17.3
3 1/2	15.4

II.A.

100 kVp, 1 cm field Added Filter mm Al	R/min
0	60.4
1/4	46.0
1/2	39.9
1	31.4
2	22.0
3	16.9
3 1/2	14.9

I.D.

50 kVp, 1 cm field Added Filter mm Al	R/min
0	24.6
1/4	15.6
1/2	12.0
1	8.3
2	4.6

5.

kVp	Field Size	1 HVL mm Al	2 HVL mm Al	Homogeneity Factor
50	4 cm	0.50	1.00	0.50
50	1 cm	0.48	0.99	0.49
50	0	0.47	0.98	0.48
100	4 cm	1.09	2.35	0.47
100	1 cm	1.07	2.32	0.46
100	0	1.06	2.29	0.46

IV. ANSWERS TO QUESTIONS

A. The half-value layer is defined as the thickness of a specified material necessary to reduce the intensity of an x-ray or γ-ray beam to one half its original value.

The first half-value layer reduces the intensity of a beam of x rays from 100 percent to 50 percent. The second half-value layer reduces the intensity of a beam of x rays from 50 percent to 25 percent.

B. The first and second HVL decrease with decreasing field size at the filter. The decrease in HVL has been found to be a linear function of the field diameter at the filter and is the result of the decreasing amounts of scattered radiation into the detector as field size decreases.

C. For a monoenergetic x-ray beam the first and second HVL's are identical because the addition of one HVL to the beam does not alter the energy spectrum of the beam.

For a heterogenous x-ray beam the first HVL is smaller than the second HVL. This condition is a direct result of the shift in the energy spectrum of the x-ray beam that occurs upon the insertion of one HVL into the beam. The effective energy of the beam after the insertion of one HVL is greater than before; thus it will take a greater thickness of absorber to reduce the beam by 50 percent, therefore, the second HVL must be larger than the first HVL.

D. The homogeneity coefficient is defined as the ratio of the first HVL to the second HVL; ($\frac{\text{1st HVL}}{\text{2nd HVL}}$). For a monoenergetic x-ray beam the homogeneity coefficient will be unity because the first and second HVL's are identical. For a heterogenous x-ray beam the homogeneity coefficient will always be less than unity because the second HVL is always larger than the first HVL. The answers to question C explain why the second HVL is larger than the first HVL.

E. $$\text{HVL} = \frac{0.693}{\mu}$$

$$\mu = \frac{0.693}{\text{HVL}}$$

From Lab data: HVL at 50 kVp = 0.47 mm Al

HVL at 100 kVp = 1.06 mm Al

ρ for aluminum = 2.7 g/cm^3

$$\frac{\mu}{\rho} = \frac{0.693}{(\rho)\ (\text{HVL})}$$

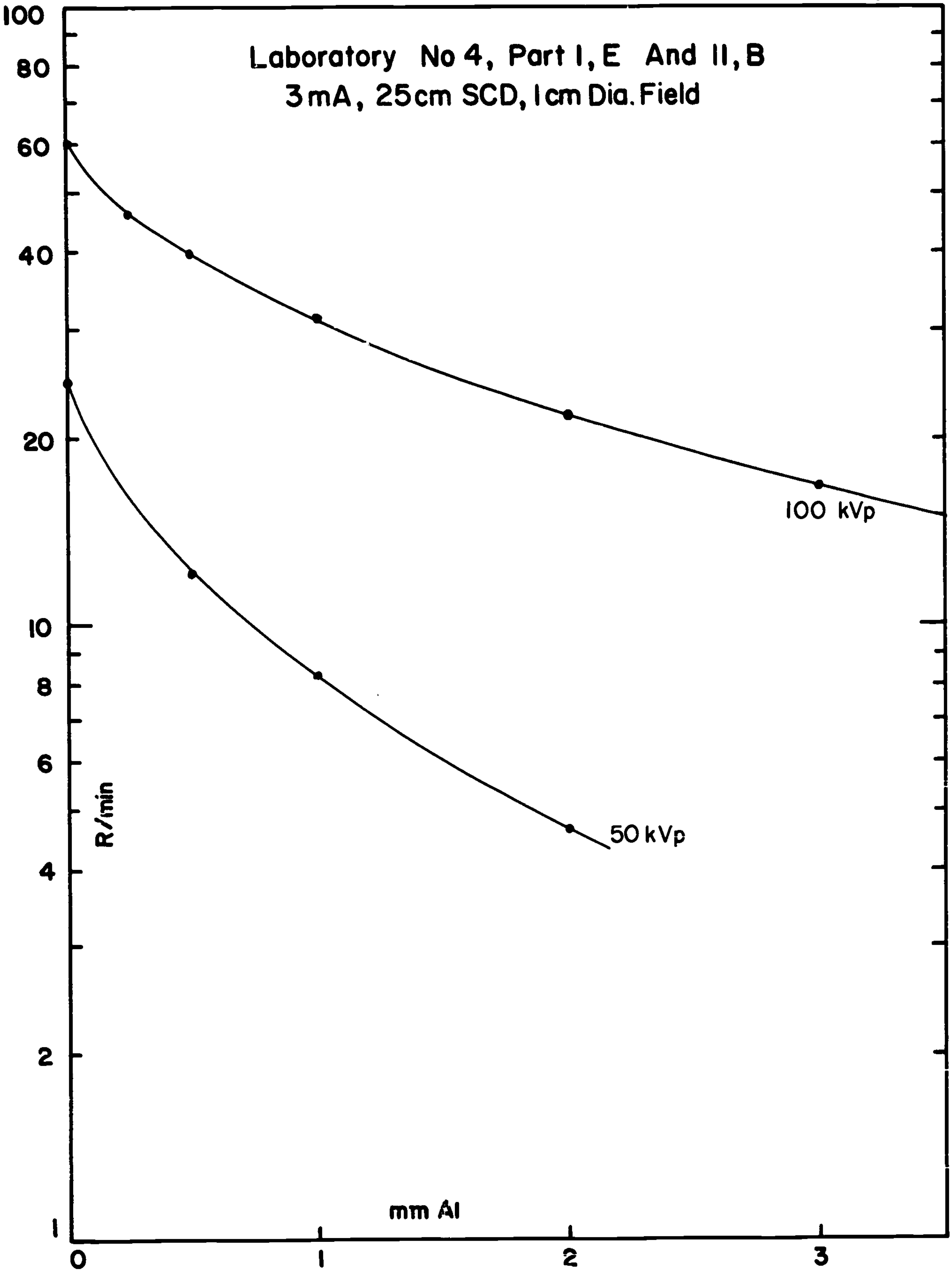
$$50\ \text{kVp:}\ \frac{\mu}{\rho} = \frac{0.693}{(2.7)\ (.047)} = 5.46\ \text{cm}^2/\text{g}$$

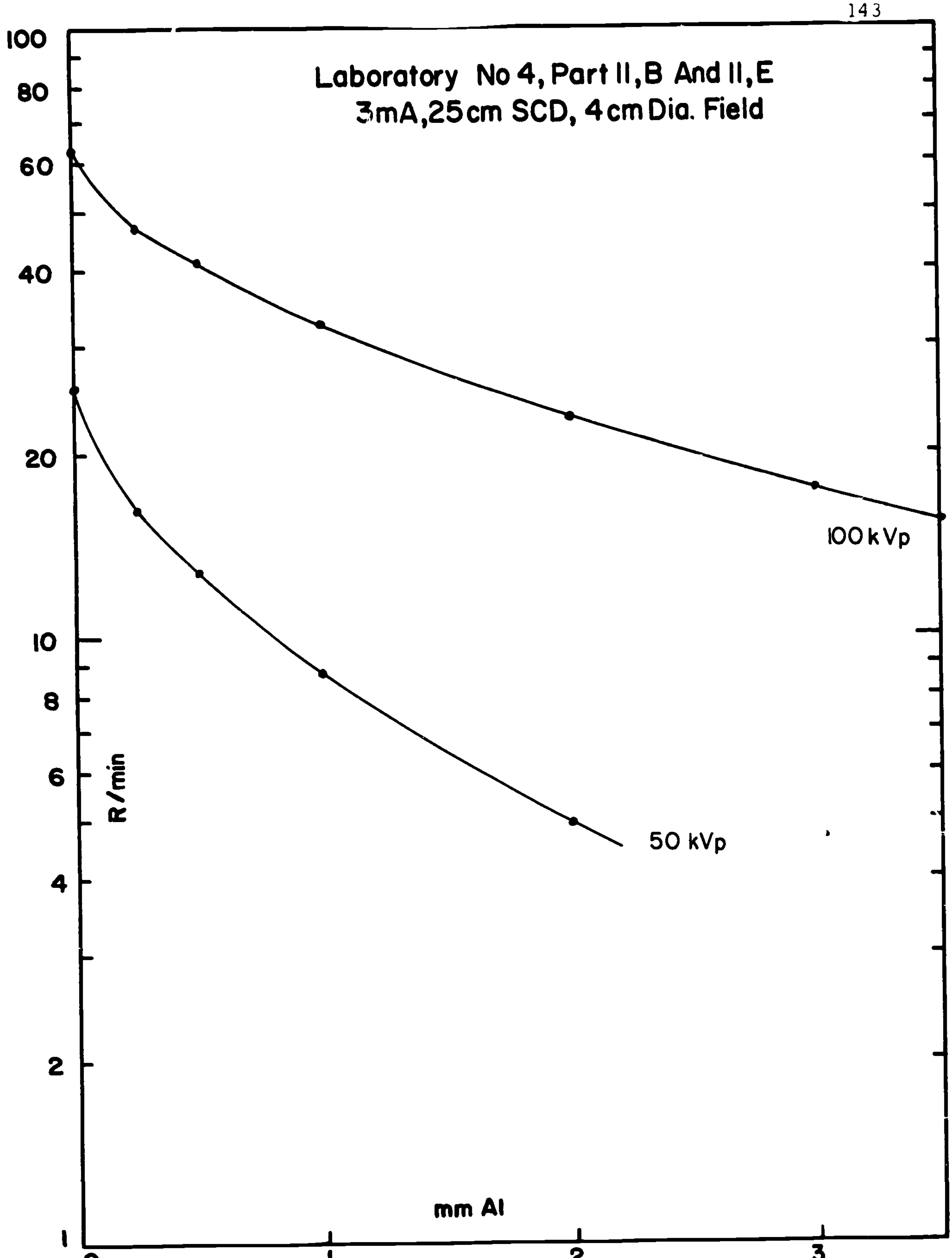
$$100\ \text{kVp:}\ \frac{\mu}{\rho} = \frac{0.693}{(2.7)\ (0.106)} = 2.42\ \text{cm}^2/\text{g}$$

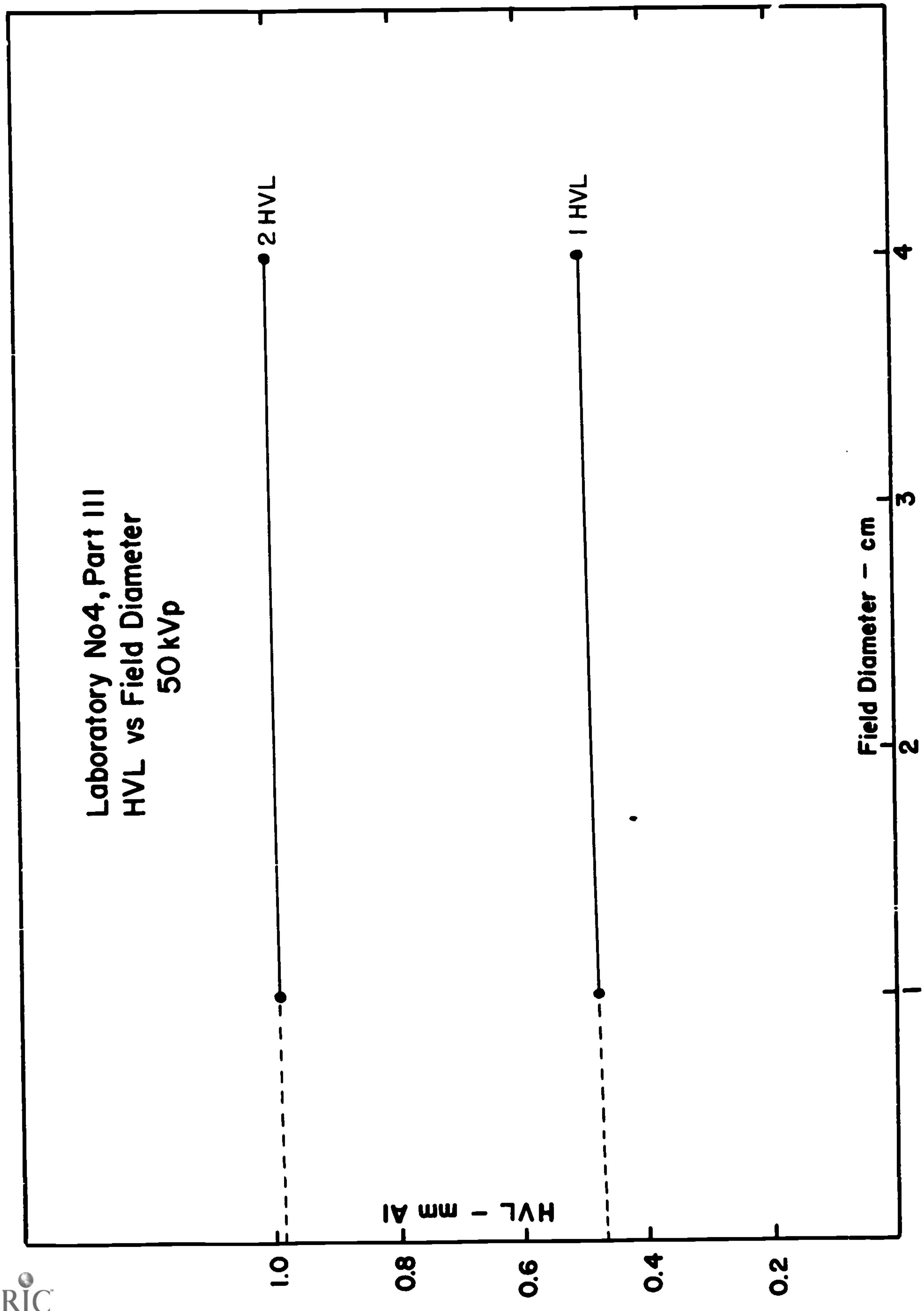
From curve:

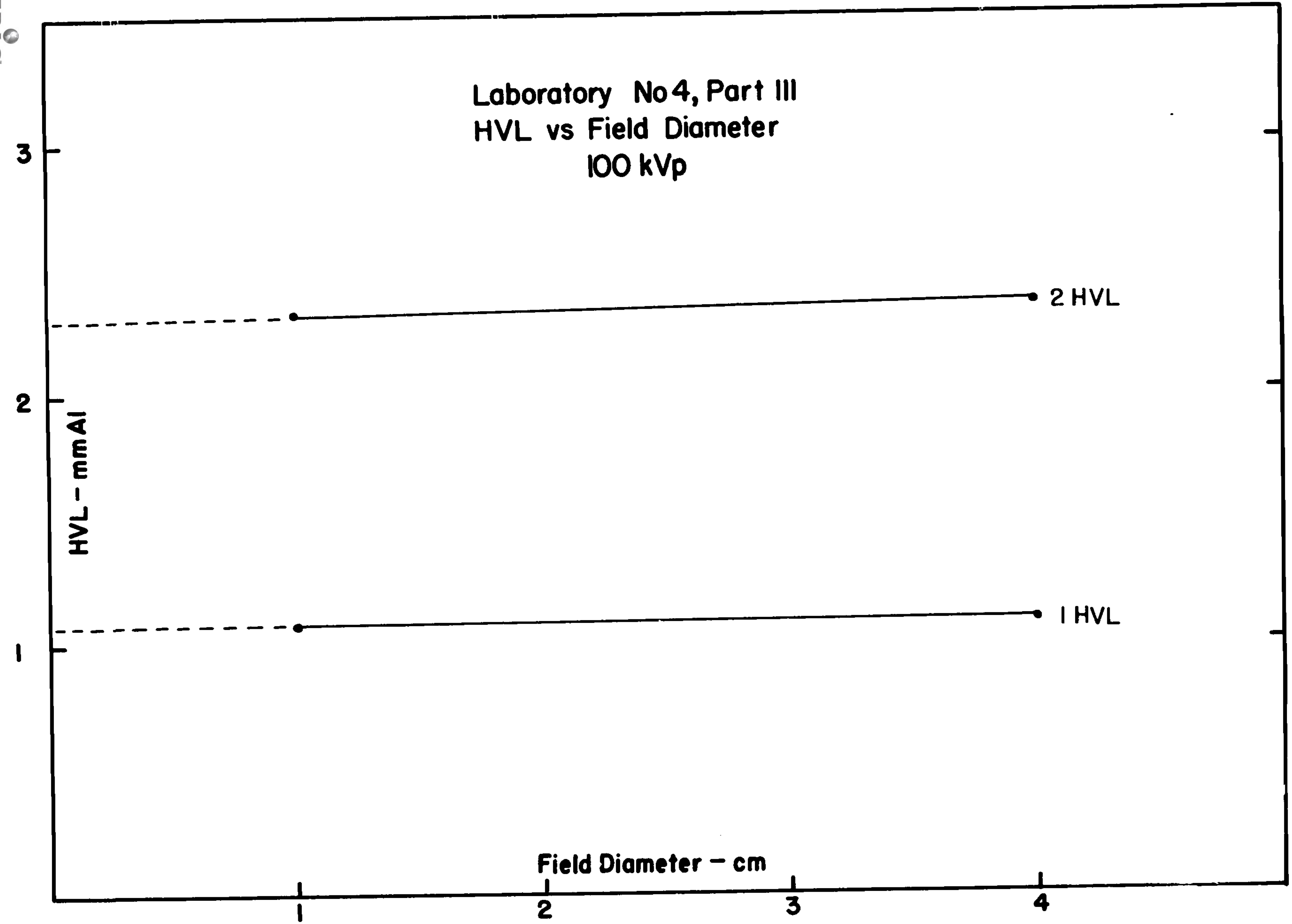
50 kVp $\rightarrow$ $\underline{\underline{\text{18 keV}}}$

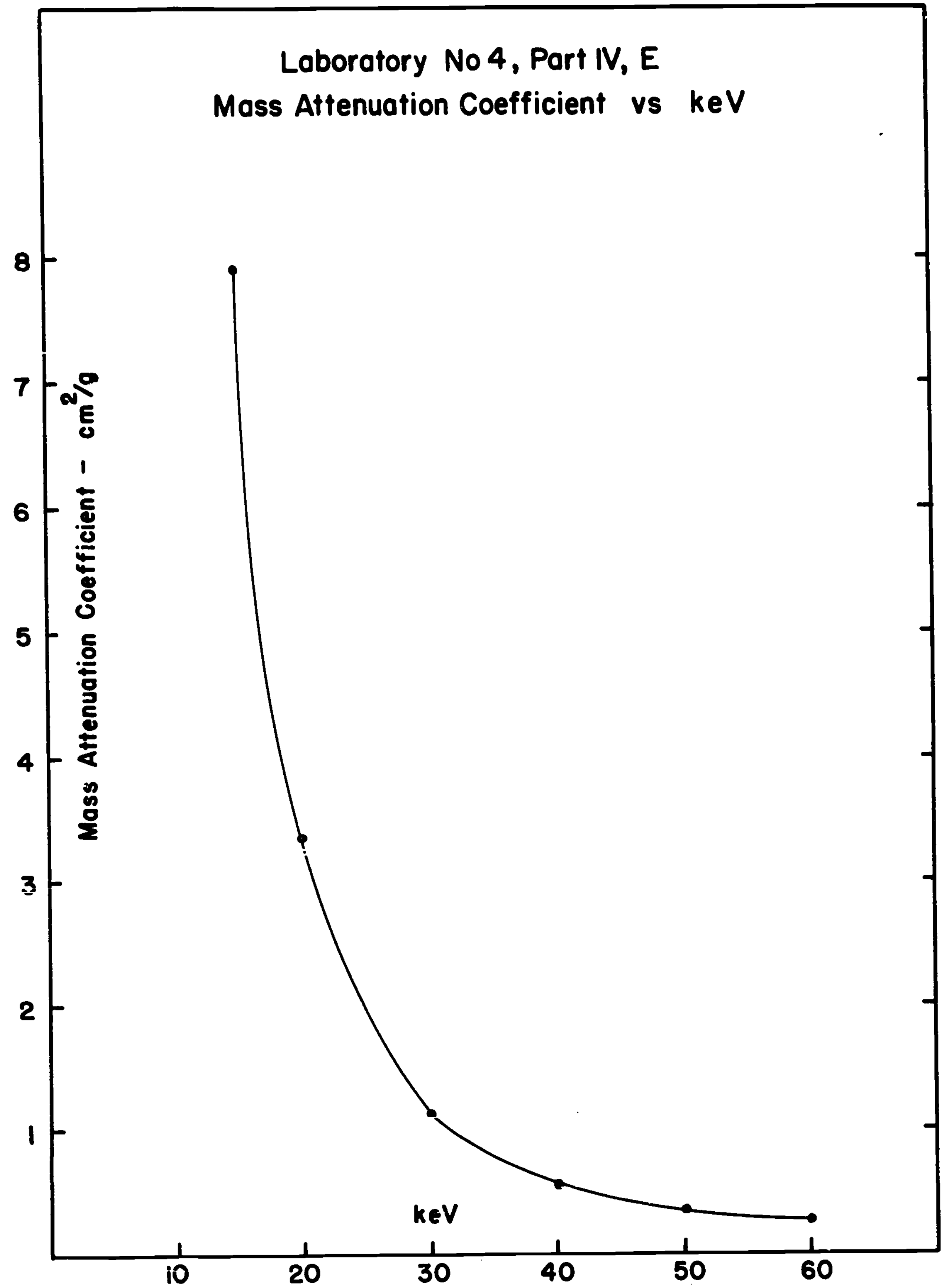
100 kVp $\rightarrow$ $\underline{\underline{\text{21 keV}}}$


Laboratory No 4, Part I, E And II, B
3 mA, 25 cm SCD, I cm Dia. Field
100
80
60
40
20
10
8
6
4
2
1
R/min
100 kVp
50 kVp
mm Al
0
1
2
3


Laboratory No 4, Part II,B And II,E
3mA,25cm SCD, 4cm Dia. Field
100
80
60
40
20
10
8
6
4
2
1
R/min
100 kVp
50 kVp
mm Al
0
1
2
3


Laboratory No4, Part III
HVL vs Field Diameter
50 kVp
2 HVL
1 HVL
HVL - mm Al
1.0
0.8
0.6
0.4
0.2
Field Diameter - cm
1
2
3
4


Laboratory No 4, Part III
HVL vs Field Diameter
100 kVp
2 HVL
1 HVL
HVL - mm Al
Field Diameter — cm
1
2
3
4
1
2
3


Laboratory No 4, Part IV, E
Mass Attenuation Coefficient vs keV
Mass Attenuation Coefficient - cm²/g
keV
8
7
6
5
4
3
2
1
10
20
30
40
50
60

LABORATORY No. 5

TITLE: Energy Dependence of X-Ray Measuring Instruments

PURPOSE: To study the energy dependence characteristics of several instruments used to measure x rays in terms of the roentgen.

TIME: Three hours

MATERIALS FOR EACH STUDENT GROUP:

One Victoreen Model 555 Radocon II with Model 555-0.1 DA probe
One General Electric 90 kVp mobile x-ray machine
One Victoreen Model 444 survey meter
One Victoreen Model 592B survey meter
One Victoreen Model 740B survey meter
One Victoreen Model 687C Minometer II
One Victoreen Model N3A 0-200 mR pocket chamber
One Bendix Model NS 0-200 mR pocket dosimeter
One Bendix Model 906-1 dosimeter charger
One Bendix 0-200 mR low energy pocket dosimeter
Two sheets linear graph paper, K & E 46-1323 or equivalent
One ships curve, K & E 1685-48 or equivalent

REFERENCES: Attix, Roesch, Tochilin
Radiation Dosimetry

Stanton, L.
Basic Medical Radiation Physics

Laboratory No. 5

ENERGY DEPENDENCE OF X-RAY MEASURING INSTRUMENTS

I. INTRODUCTION

There are several factors which may result in the failure of a radiation measuring instrument to indicate the true exposure in a radiation field. These include time response, temperature and pressure (for unsealed chambers), field distribution and photon energy. The purpose of this laboratory exercise is to investigate the dependence of several x-ray measuring instruments on one of these factors, photon energy.

An x-ray measuring instrument is said to exhibit energy dependence if the ratio of true exposure to indicated exposure is not unity as a function of energy. Factors contributing to energy dependence of instruments include:

1. Improper chamber wall thickness
2. Non air-equivalent chamber wall

Ion chambers are usually designed for operation over a specified energy range with a specified energy response (±2%, ±5%, ±10%, etc.) over this range. Except for the Victoreen 444 survey meter, the instruments investigated are not designed for use in the low energy range provided by the 90 kVp x-ray machine used in this laboratory exercise. As a result, there are significant changes in instrument response over the range of x-ray energies used in this laboratory exercise.

II. EQUIPMENT

A. General Electric 90kVp mobile x-ray machine

B. Victoreen Model 555 Radocon II with Model 555-0.1DA probe

C. Victoreen Model 444 survey meter

D. Victoreen Model 592B survey meter

E. Victoreen Model 740B survey meter

F. Victoreen Model 687C Minometer II

G. Victoreen Model N3A 0-200 mR pocket chamber

H. Bendix Model 906-1 dosimeter charger/reader

I. Bendix Model NS 0-200 mR dosimeter

J. Bendix Model 1200-MR 0-200mR dosimeter

III, INTEGRATING INSTRUMENTS

CAUTION: Special consideration must be paid to the protection of personnel whenever x-ray equipment is operated outside a shielded enclosure. The use of mobile protective shields and the wearing of protective aprons can be effective in providing adequate personnel protection.

A. Expose the 555 Radocon II on the 0-300 mR scale, the Victoreen 444 on the 0-300 mR scale, the self-reading pocket dosimeters and the pocket chamber at the following settings:

kVp	mA	Added mm Al Filter	Effective Energy-keV
50	3	0	14.5
60	3	0	15.0
90	3	0	16.5
50	3	0.5	20.5
70	3	0.5	22.5
85	3	0.5	23.5
70	3	1.0	24.5
85	3	1.0	26.5
70	3	2.0	29.0
90	3	3.0	30.5

B. Select distance and exposure times to provide a 1/2 scale response using the 555 Radocon II.

C. Calculate the correction factors for each instrument using the 555 Radocon as the standard. (The correction factor for the 555 Radocon II is essentially unity over the energy range involved here).

$$\text{Correction Factor} = \frac{\text{555 Radocon Reading}}{\text{Instrument Reading}}$$

D. On the same sheet of graph paper plot correction factors vs keV for each instrument used.

IV. SURVEY INSTRUMENTS

A. Expose the 555 Radocon and the survey instruments to the same x-ray machine settings used in Section III.

B. Choose a distance to provide 1/2 - 2/3 full scale response on the 555 Radocon.

C. Calculate correction factors for each instrument using the 555 Radocon as a standard.

D. Plot correction factors vs keV as in Section III.

V. QUESTIONS

A. Explain how one would use these experimental results in actual practice.

B. Why does the model NS pocket dosimeter have poorer energy dependence characteristics than the pocket chamber?

Laboratory No. 4

Data Sheet

I. INTEGRATING INSTRUMENTS

Effective Energy keV	Exposure Time sec	Radocon 555 mR	Victoreen 444 mR	Victoreen 444 C.F.	Vict. N3A Pocket Cham. mR	Vict. N3A Pocket Cham. C.F.	Bendix NS Dosimeter mR	Bendix NS Dosimeter C.F.	Bendix 1200-MR Pocket Dosim. mR	Bendix 1200-MR Pocket Dosim. C.F.
14.5										
15.0										
16.5										
20.5										
22.5										
23.5										
24.5										
26.5										
29.0										
30.5										

II. SURVEY (Rate) INSTRUMENTS

Effective Energy keV	Radocon 555 mR/h	Victoreen 444 mR/h	Victoreen 444 C.F.	Victoreen 740 mR/h	Victoreen 740 C.F.	Victoreen 592B mR/h	Victoreen 592B C.F.
14.5							
15.0							
16.5							
20.5							
22.5							
23.5							
24.5							
26.5							
29.0							
30.5							

Laboratory No. 5

TYPICAL DATA

I. INTEGRATING INSTRUMENTS

Effective Energy keV	Radocon 555		Victoreen 444		Bendix NS Dosimeter		Vict. N3A Chamber		Bendix 1200-MR Dosimeter	
	mR	C.F.	mR	C.F.	mR	C.F.	mR	C.F.	mR	C.F.
14.5	150	1.00	125	1.20	18	8.35	54	2.78	139	1.08
15.0	150	1.00	125	1.20	24	6.28	57.5	2.57	139	1.08
16.5	150	1.00	127	1.18	34.5	4.32	65.5	2.30	143	1.05
20.5	150	1.00	131	1.14	47	3.20	83	1.80	149	1.01
22.5	150	1.00	135	1.11	52	2.90	94	1.60	150	1.00
23.5	150	1.00	137	1.10	54.5	2.75	97	1.55	150	1.00
24.5	150	1.00	139	1.08	66	2.28	103	1.45	150	1.00
26.5	150	1.00	147	1.02	86	1.75	106	1.41	150	1.00
29.0	150	1.00	150	1.00	99	1.51	117	1.28	151	0.99
30.5	150	1.00	153	0.98	120	1.25	131	1.15	152	0.99

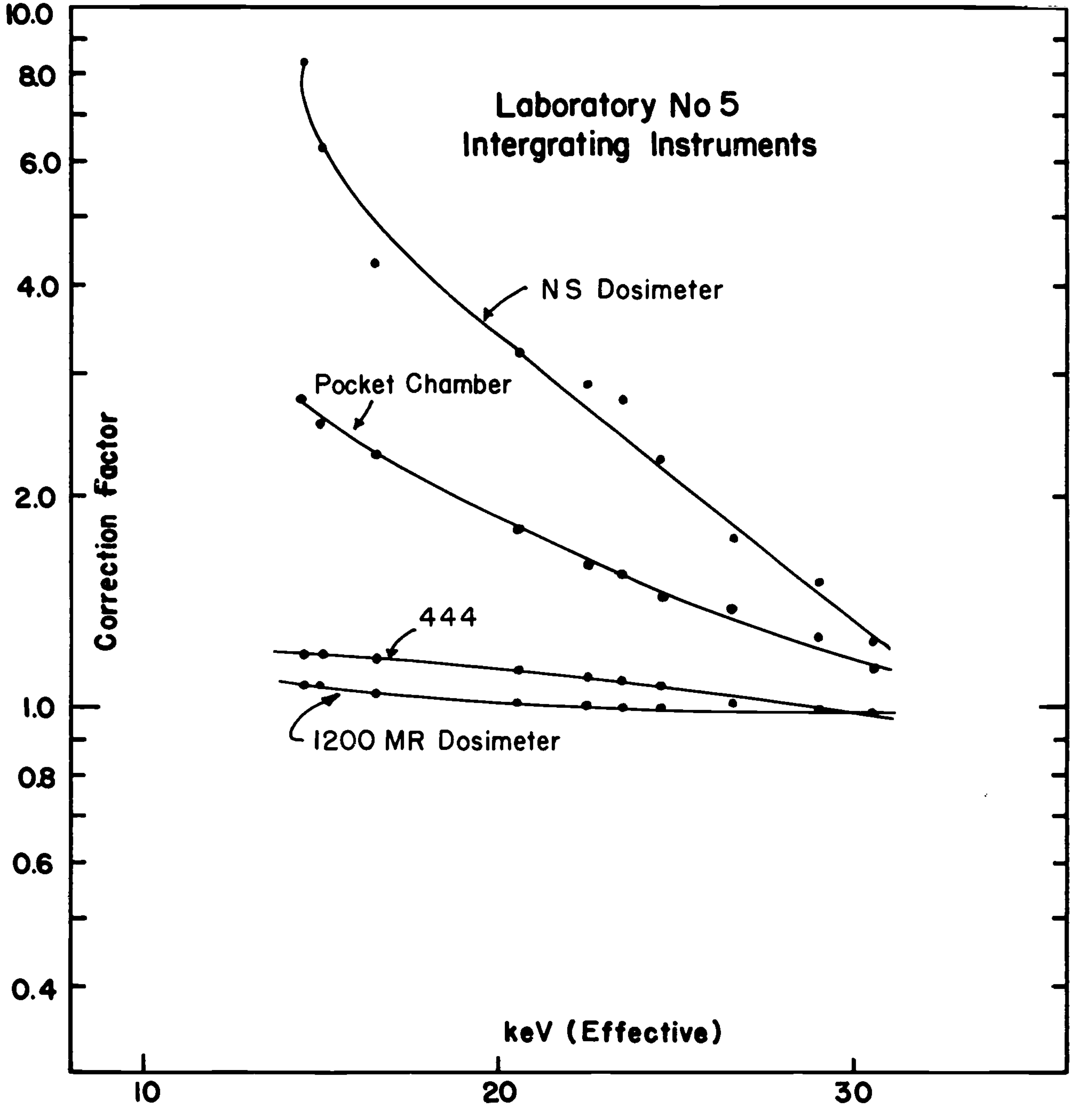
II. SURVEY INSTRUMENTS

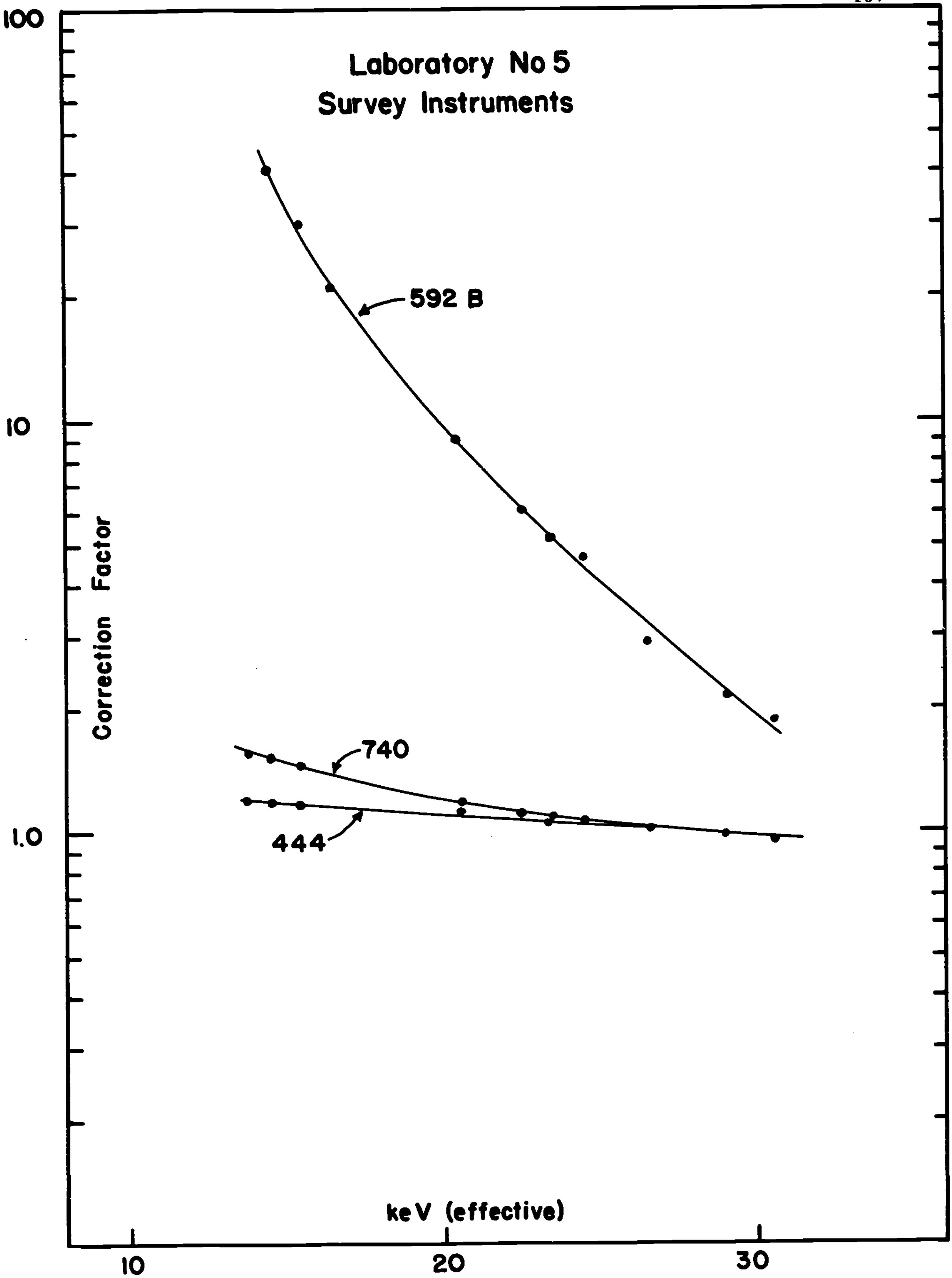
Effective Energy keV	Radocon 555 R/h	Radocon 555 C.F.	Victoreen 444 R/h	Victoreen 444 C.F.	Victoreen 740 R/h	Victoreen 740 C.F.	Victoreen 592B R/h	Victoreen 592B C.F.
14.5	0.96		0.80	1.20	0.63	1.52	0.024	40.7
15.0	0.75		0.63	1.19	0.49	1.52	0.025	30.2
16.5	1.50		1.26	1.18	1.03	1.45	0.072	21.0
20.5	2.25		1.96	1.15	1.87	1.20	0.25	9.00
22.5	1.45		1.32	1.10	1.29	1.12	0.24	6.10
23.5	1.50		1.37	1.10	1.37	1.10	0.29	5.20
24.5	1.90		1.78	1.07	1.78	1.07	0.41	4.67
26.5	1.90		1.86	1.02	1.86	1.02	0.65	2.92
29.0	1.60		1.60	1.00	1.62	0.99	0.75	2.14
30.5	1.30		1.32	0.99	1.33	0.98	0.70	1.87

III. Answers to Questions

A. If the effective energy of the radiation source is known, these data would tell which instrument to use without a significant correction factor or what the correction factor is for a particular instrument. If the range of energies only is known the data would tell which instrument to use for the greatest overall accuracy.

B. The NS pocket dosimeter is not designed for use below about 80 keV whereas the pocket chamber is designed for use down to 30 keV. The wall of the pocket dosimeter is not "air equivalent" (it is too thick) at the low energies.


Laboratory No 5
Intergrating Instruments
NS Dosimeter
Pocket Chamber
444
1200 MR Dosimeter
Correction Factor
keV (Effective)
10.0
8.0
6.0
4.0
2.0
1.0
0.8
0.6
0.4
10
20
30



Laboratory No 5
Survey Instruments
592 B
740
444
Correction Factor
keV (effective)
100
10
1.0
10
20
30

LABORATORY NO. 6

TITLE: Response Time of Survey Instruments

PURPOSE: To determine the response time of typical survey instruments

TIME: Three hours

MATERIALS FOR EACH STUDENT GROUP:

One General Electric 90 kVp mobile X-ray machine

One Victoreen model 440 survey meter

One Victoreen model 740 survey meter

One Victoreen model 444 survey meter

One Victoreen model 592B survey meter

Four sheets linear graph paper

One ships curve

REFERENCES: Survey meter instruction manuals

LABORATORY NO. 6

Survey Instrument Response Time

I. Introduction

The survey instruments that will be used in this laboratory exercise are devices which measure the current produced by ionization within a confined volume of air. This current is proportional to exposure rate and the readout is in this form. For a particular exposure rate it takes the instrument a certain time to reach a final steady-state reading. This response time is influenced by two factors:

1. The R C time constant of the circuit and,
2. The inertia of the meter movement

The R C time constant is usually the limiting factor. The time constant, resistance in ohms times capacitance in farads, is that time in seconds for the meter to indicate 63% of its final steady-state reading (assuming no meter movement inertia effects). In ionization chamber survey meters, C is the sum of the chamber capacitance and the distributed capacitance of the associated circuitry, and R is usually the chamber load resistor. In this type of instrument, the sensitivity is often changed by switching in more or less load resistance. Therefore, the time constant may be different from one range (sensitivity) to another. A simplified diagram is shown in Figure 1 (V (t) refers to the voltage at time t).

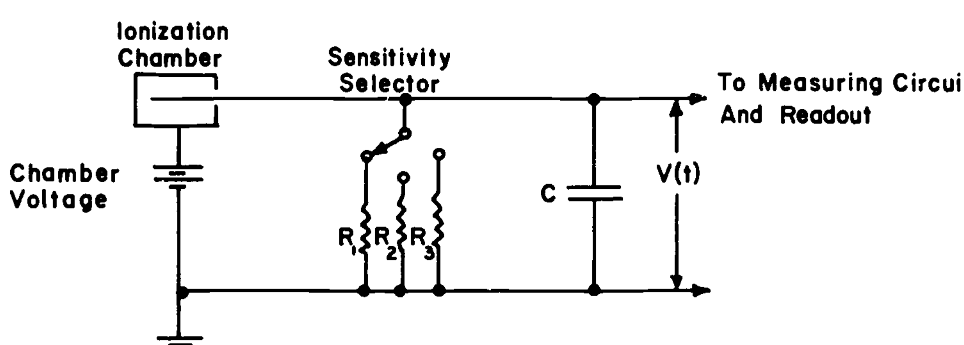


Figure 1

The voltage V(t) is directly proportional to the meter reading. If V(f) is the final steady-state value for a particular ionization current, then V(t) is given by:

$$V(t) = V(f)\ (1 - e^{-t/RC})$$

The ratio V(t) / V(f) represents the fraction of the final steady-state value as read on the meter. When t = RC = time constant:

$$\frac{V(t)}{V(f)} = (1 - e^{-1}) = 1 - 0.37 = 0.63$$

If the percent of steady-state reading vs exposure time is plotted, the time constant can be determined from the curve where the meter response is 63% of the final steady-state value. Meter movement inertia will cause this curve to deviate from the ideal.

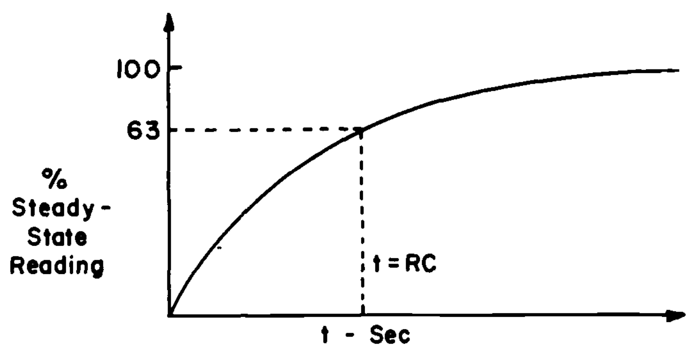


Figure 2

II. Equipment

A. General Electric 90 kVp mobile x-ray machine

B. Victoreen survey meters

1. Model 440
2. Model 740
3. Model 444
4. Model 592B

III. Procedure

Caution: Special consideration must be paid to the protection of personnel whenever x-ray equipment is operated outside a shielded enclosure. The use of mobile protective shields and wearing of protective aprons can be effective in providing adequate personnel protection.

A. Adjust the x-ray machine settings (kVp, mA) and geometry (filter and distance) to provide full-scale response for each range on each survey meter used.

B. Determine the time response of the survey meters by recording the meter readings at exposure times from 0.1 second to a time at least equal to the time necessary for steady-state response (this may require times up to 30 sec.).

C. On long exposures where the meter may reach a peak reading and then decrease to a steady-state value, record both these values.

D. Plot response curves for each of the survey meters, percent steady-state reading vs exposure time, and determine the time constant for each meter scale.

IV. <u>Questions</u>

A. Of what importance is a knowledge of the time response characteristics of survey meters in the selection of a survey meter for a particular application?

B. Why is it desirable to have a complete time response curve rather than only the value of the survey meter time constant?

C. In changing to a more sensitive scale (e.g. from 100 mR/h to 3 mR/h) will the value of the load resistor increase or decrease? Explain.

LABORATORY NO. 6

Data Sheets

I. Victoreen 740 Survey Meter

Scale								
25 mR/h (X 1)			250 mR/h (X 10)			2500 mR/h (X 100)		
Time-sec	Reading	%FS	Time-sec	Reading	%FS	Time-sec	Reading	%FS

II. Victoreen 440 Survey Meter

Scale								
3 mR/h			10 mR/h			30 mR/h		
Time	Reading	%FS	Time	Reading	%FS	Time	Reading	%FS

Scale					
100 mR/h			300 mR/h		
Time	Reading	% FS	Time	Reading	%FS

III. Victoreen 444 Survey Meter

Scale								
3 mR/h			10 mR/h			30 mR/h		
Time	Reading	%FS	Time	Reading	%FS	Time	Reading	%FS

Scale					
100 mR/h			300 mR/h		
Time	Reading	%FS	Time	Reading	%FS

IV. Victoreen 592B Survey Meter

Scale								
10 mR/h (X1)			100 mR/h (X10)			1000 mR/h (X100)		
Time	Reading	%FS	Time	Reading	%FS	Time	Reading	%FS

Laboratory No. 6

TYPICAL DATA

I. Victoreen 740 Survey Meter

Scale

25 mR/h (X1)			250 mR/h (X 10)			2500 mR/h (X 100)		
Time-sec	Reading	%	Time-sec	Reading	%	Time-sec	Reading	%
1	2	10.5	0.2	20	10	0.3	375	17.5
2	4	20.5	0.5	45	22	0.5	600	28
3	6	31	0.8	75	36.5	0.8	900	42
4	7.5	38.5	1	90	44	1.1	1150	53.5
5	9	46	1.3	115	56	1.4	1350	62.5
7	11.8	60.5	1.6	135	66	1.8	1550	72
9	14	72	2	150	73	2.3	1750	81.5
10.5	15	77	2.3	160	78	2.8	1950	91
12.5	17.5	90	2.8	175	85.5	3.5	2050	95.5
16	19.5	100	3	175	85.5	4	2150	100
20	20.3	104	3.5	200	97.5	4.5	2150	100
24	19.5	100	4	195	95	5	2150	100
28	19.5	100	4.5	195	95	6	2150	100
32	19.5	100	5.5	200	97.5	7	2150	100
			6	205	100			
			6.5	205	100			
			10	205	100			

II. Victoreen 440 Survey Meter

3 mR/h			10 mR/h			30 mR/h		
Time-sec	Reading	%	Time-sec	Reading	%	Time-sec	Reading	%
0.5	0.31	14	0.3	1.8	21.5	0.4	7.9	31.5
0.8	0.52	23.5	0.5	2.7	32	0.5	8.5	34
1	0.70	32	0.8	3.9	46.5	0.8	14.5	57.5
1.3	0.91	41.5	1	5.0	59.5	1	16.5	65.5
1.5	0.95	43	1.2	5.4	64.5	1.3	20	79.5
2	1.22	55.5	1.5	6.4	76	1.5	22.5	84.5
2.5	1.46	66.5	1.8	6.9	82	1.8	24.1	95.5
3	1.50	68.8	2	7.0	83.5	2	25.0	99
3.5	1.64	74.5	2.5	7.6	91.5	2.5	26.0	103
4	1.8	82	3	7.8	93	3	26.0	103
5	1.92	87	3.5	8.1	96.5	3.5	25.2	100
6	2.15	97.5	4	8.2	97.5	4	25.2	100
7	2.20	100	4.5	8.4	100	5	25.2	100
8	2.20	100	5	8.6	102.5			
9	2.20	100	6	8.3	99			
10	2.20	100	7	8.4	100			
			10	8.4	100			

II. Victoreen 440 Survey Meter (continued)

Scale

100 mR/h			300 mR/h		
Time-sec	Reading	%	Time-sec	Reading	%
0.3	24	24.5	0.3	68	25.5
0.5	38	39	0.5	105	39
0.8	61	62	0.8	155	57.5
1	73	74.5	1	188	70
1.5	98	100	1.5	240	89
2	103	105	2	265	99
3	98	100	2.5	262	97.5
3.5	97	99	3	280	104
4	98	100	3.5	267	99
5	98	100	4	269	100
			5	269	100

III. Victoreen 444 Survey Meter

Scale								
3 mR/h			10 mR/h			30 mR/h		
Time-sec	Reading	%	Time-sec	Reading	%	Time-sec	Reading	%
0.5	0.5	18.5	1	2.5	29	0.5	5	20
1	1.1	40.5	2	4.5	52.5	1	10	39.5
1.5	1.65	61	3	5.7	66.5	1.5	14.2	56
2	1.84	68	4	7.1	82.5	2	18	71
2.5	2.25	83.5	5	7.4	86	2.5	20	79
3	2.52	93.5	6	8.0	93	3	22.5	89
3.5	2.55	94.5	7	8.5	99	3.5	25	99
4	2.70	100	8	8.3	96.5	4	25	99
4.5	2.75	102	9	8.6	100	4.5	26	103
5	2.70	100	10	8.6	100	5	25.4	101
5.5	2.70	100				5.5	25.2	99.5
						6	25.3	100

III. Victoreen 444 Survey Meter (continued)

Scale					
100 mR/h			300 mR/h		
Time-sec	Reading	%	Time-sec	Reading	%
0.5	26	30	0.5	75	30
1	48.5	55	1	140	56.5
1.5	66	76	1.5	185	74.5
2	77	87.5	2	220	88.5
2.5	82.5	94	2.5	235	95
3	86.5	98.5	3	242	97
4	88.5	101	3.5	246	99
5	88.2	100.5	4	252	102
6	88	100	4.5	252	102
7	88	100	5	246	99
8	88	100	6	247	99.5
10	88	100	7	248	100
			10	248	100

IV. Victoreen 592B Survey Meter

10 mR/h (X1)			100 mR/h (X10)			1000 mR/h (X100)		
Time-sec	Reading	%	Time-sec	Reading	%	Time-sec	Reading	%
0.5	3.4	38.5	0.2	23	27	0.2	250	28
1	5.7	65	0.5	46	53.5	0.5	520	58
1.5	7.3	83	0.8	64	74.5	0.8	700	78
2	8.1	92	1	71	82.5	1	760	84.5
2.5	8.3	94.5	1.5	81	94	1.5	860	95.5
3	8.5	96.5	2	84	99	2	880	98
3.5	8.8	100	2.5	87	101	2.5	910	101
4	9.0	102.5	3	86	100	3	910	101
4.5	9.0	102.5	3.5	86	100	4	900	100
5	8.8	100	4	86	100	5	900	100
6	8.8	100	5	86	100			

V. Survey Meter Time Constant

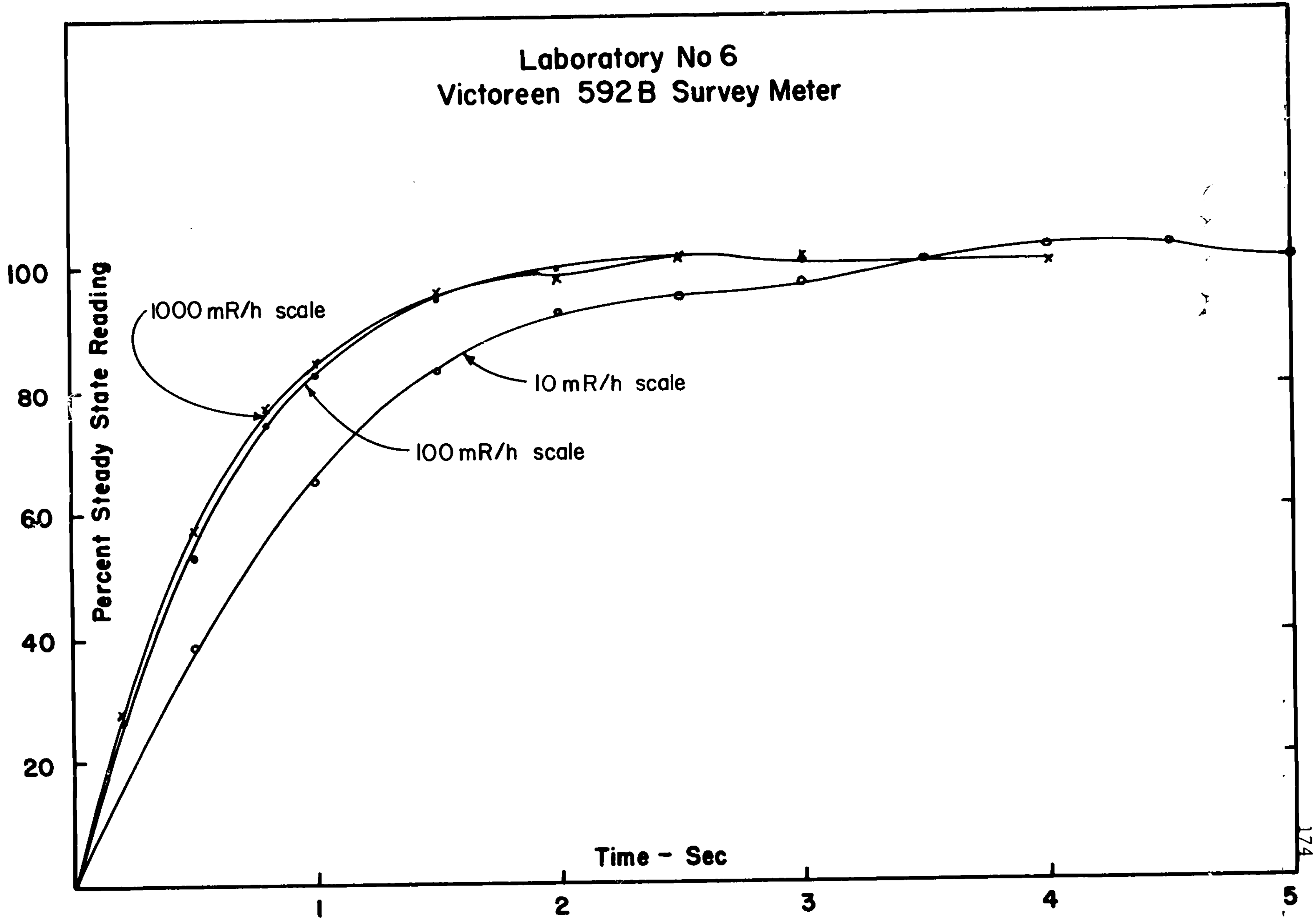
Instrument	Range	Time Constant-sec
Victoreen 740	25 mR/h (x1)	7.5
Victoreen 740	250 mR/h (x10)	1.6
Victoreen 740	2500 mR/h (x100)	1.4
Victoreen 440	3 mR/h	2.4
Victoreen 440	10 mR/h	1.1
Victoreen 440	30 mR/h	0.9
Victoreen 440	100 mR/h	0.8
Victoreen 440	300 mR/h	0.9
Victoreen 444	3 mR/h	2.6
Victoreen 444	10 mR/h	1.6
Victoreen 444	30 mR/h	1.6
Victoreen 444	100 mR/h	1.2
Victoreen 444	300 mR/h	1.2
Victoreen 592B	10 mR/h (x1)	0.95
Victoreen 592B	100 mR/h (x10)	0.65
Victoreen 592B	1000 mR/h (x1000)	0.55

VI. Answers to Questions

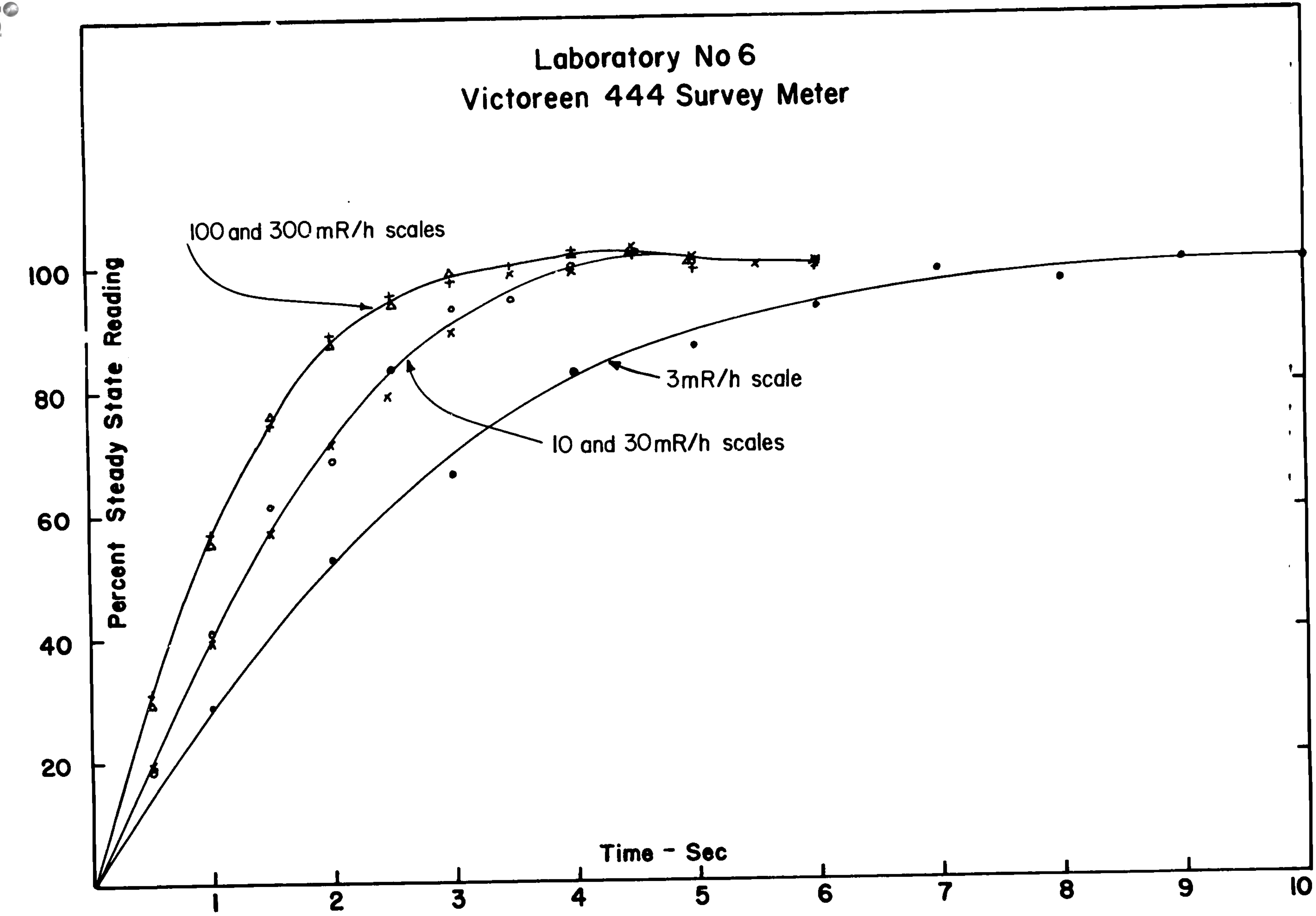
A. The duty cycle limitation of the source of radiation being surveyed may be such that radiation can only be produced for short periods of time. If the radiation "on" time is sufficiently short, the survey meter will not reach full response before the exposure is terminated. One must, therefore, know the response characteristics of the instrument in order to determine the actual value of the measured exposure rate.

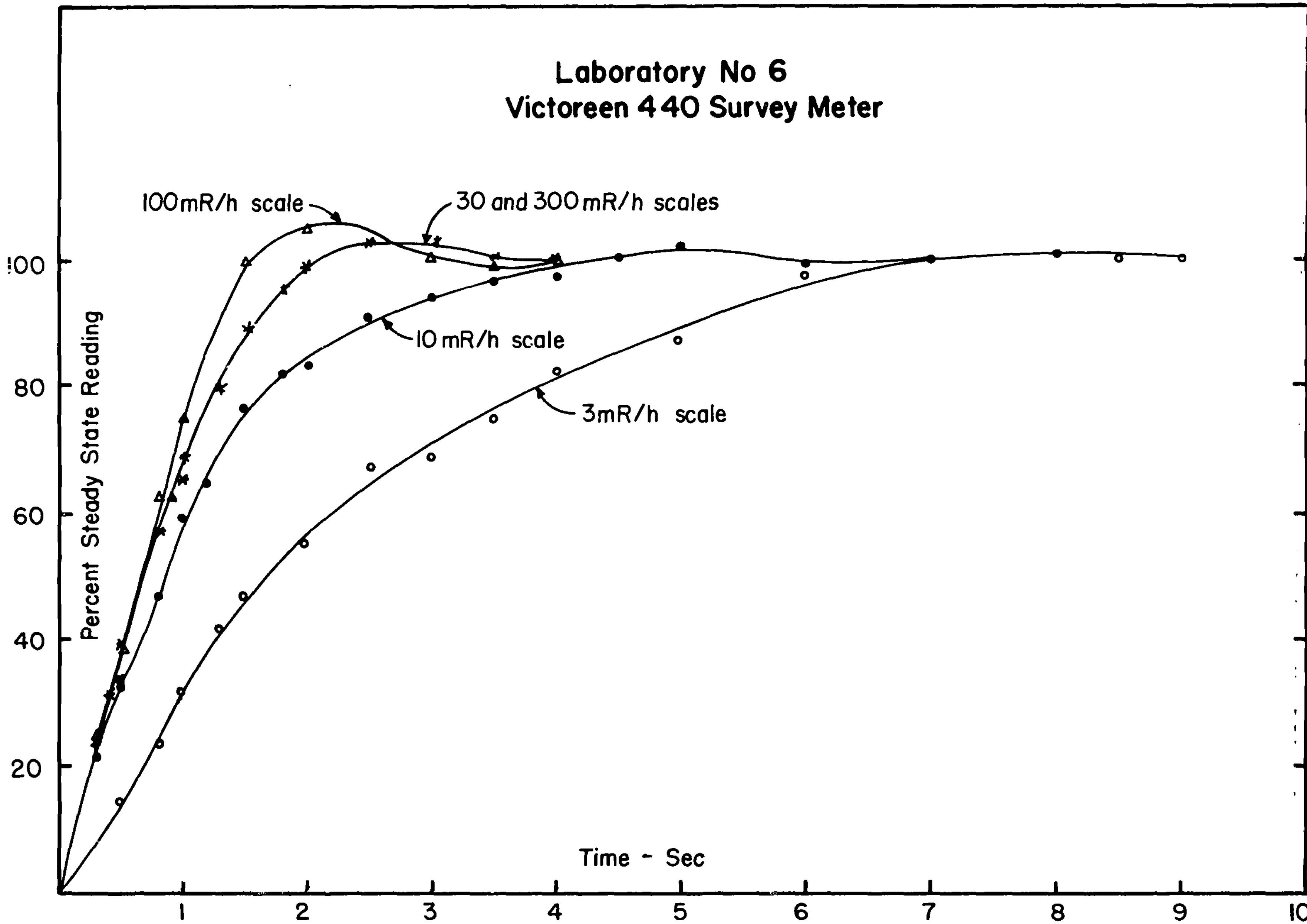
B. The time constant gives only the time required for the instrument to reach 63% of full response. One must have the entire response curve if accurate time-response corrections are to be applied.

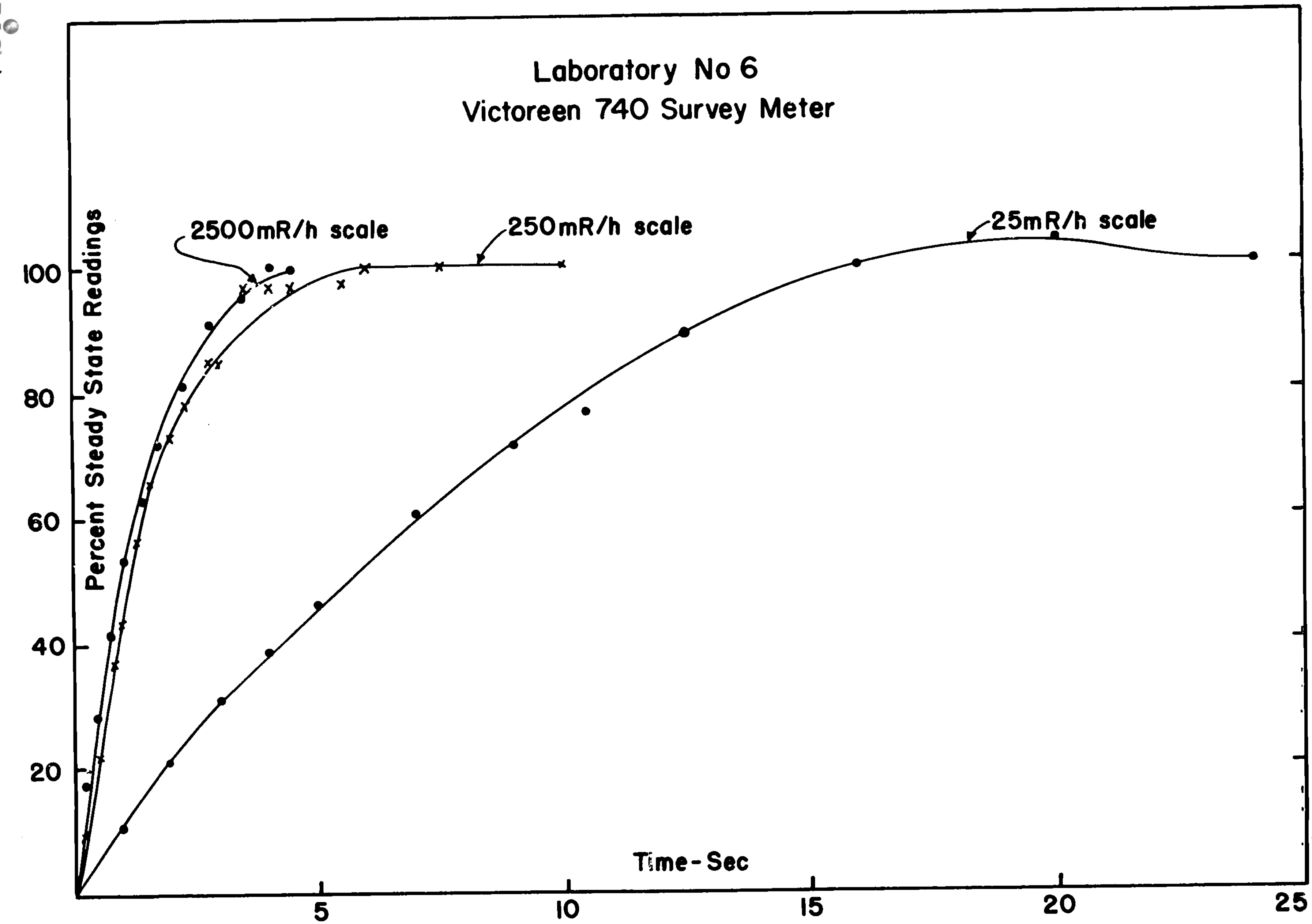
C. When changing from 100 mR/h to 3 mR/h the value of the load resistor will increase by a factor of approximately 33 1/3. The voltage signal supplied by the ionization current circuit to the amplifier portion of the survey meter is a function of the ionization current and load resistor (E = IR). For the same output meter deflection, therefore, the resistance must increase as current decreases.



Laboratory No 6
Victoreen 592 B Survey Meter
1000 mR/h scale
100 mR/h scale
10 mR/h scale
Percent Steady State Reading
100
80
60
40
20
Time - Sec
1
2
3
4
5


Laboratory No 6
Victoreen 444 Survey Meter
100 and 300 mR/h scales
10 and 30 mR/h scales
3 mR/h scale
Percent Steady State Reading
100
80
60
40
20
Time - Sec
1
2
3
4
5
6
7
8
9
10


Laboratory No 6
Victoreen 440 Survey Meter
100mR/h scale
30 and 300 mR/h scales
10 mR/h scale
3mR/h scale
Percent Steady State Reading
Time - Sec
100
80
60
40
20
1
2
3
4
5
6
7
8
9
10


Laboratory No 6
Victoreen 740 Survey Meter
2500mR/h scale
250mR/h scale
25mR/h scale
Percent Steady State Readings
100
80
60
40
20
Time-Sec
5
10
15
20
25

LABORATORY NO. 7

TITLE: Measurement of X-Ray Exposure with Personal Monitoring Film

PURPOSE: To study the techniques used to measure x-ray exposure with personal monitoring film.

TIME: Two sessions of two hours each

MATERIALS FOR EACH STUDENT GROUP:

- One Teaching X-Ray Unit
- One Kodak model 4L dental processing hanger
- Fourteen Kodak personal monitoring films--Type 2
- One Victoreen model 687 C-Minometer II
- Two Victoreen model N3A 0-200 mR pocket chambers
- One MacBeth model TD-102 densitometer
- One film processing station
- One lead sheet 4" x 6" x 1/32" thick
- One sheet linear graph paper, K & E 46-0703 or equivalent
- One ships curve, K & E 1685-48 or equivalent

REFERENCES:

Attix, Roesch, Tochilin
Radiation Dosimetry

Hine and Brownell
Radiation Dosimetry

NBS Handbook 57

Laboratory No. 6

MEASUREMENT OF X-RAY EXPOSURE WITH FILM

I. INTRODUCTION

To study the techniques used to measure x-ray exposure with personal monitoring film.

II. EQUIPMENT

A. Teaching X-Ray Unit

B. Nine personal monitoring film packets

C. Densitometer

D. One film hanger

E. Two 0-200 mR pocket chambers and charger-reader

F. One film processing station

G. One lead sheet

III. PROCEDURE

A. Number the films in the upper right-hand corner from one to nine.

B. Make the following exposures with the film packets placed on the center of the lead sheet with a pocket chamber on either side of the film to measure the exposure. Record the average of the two pocket chamber readings.

1. X-ray machine settings

   60 kVp

   1.0 mA

   3 mm Al added filtration

2. Film exposures

Film No.	Approximate mR
1	15
2	30
3	45
4	60
5	75
6	90
7	110
8	130
9	Will be used as control. It is to be kept with the other films and not exposed to direct x rays.

C. Develop the nine films plus five others to be obtained from the instructor. The additional five films have been exposed to radiation and the student will attempt to determine the exposures.

D. Film processing

1. Develop for five minutes at 68° F
2. Rinse for 30 seconds
3. Fix for ten minutes

4. Wash for 30 minutes

5. Dry

E. Read and record the film densities.

F. Calculate net densities by subtracting the control film density from each of the other film densities.

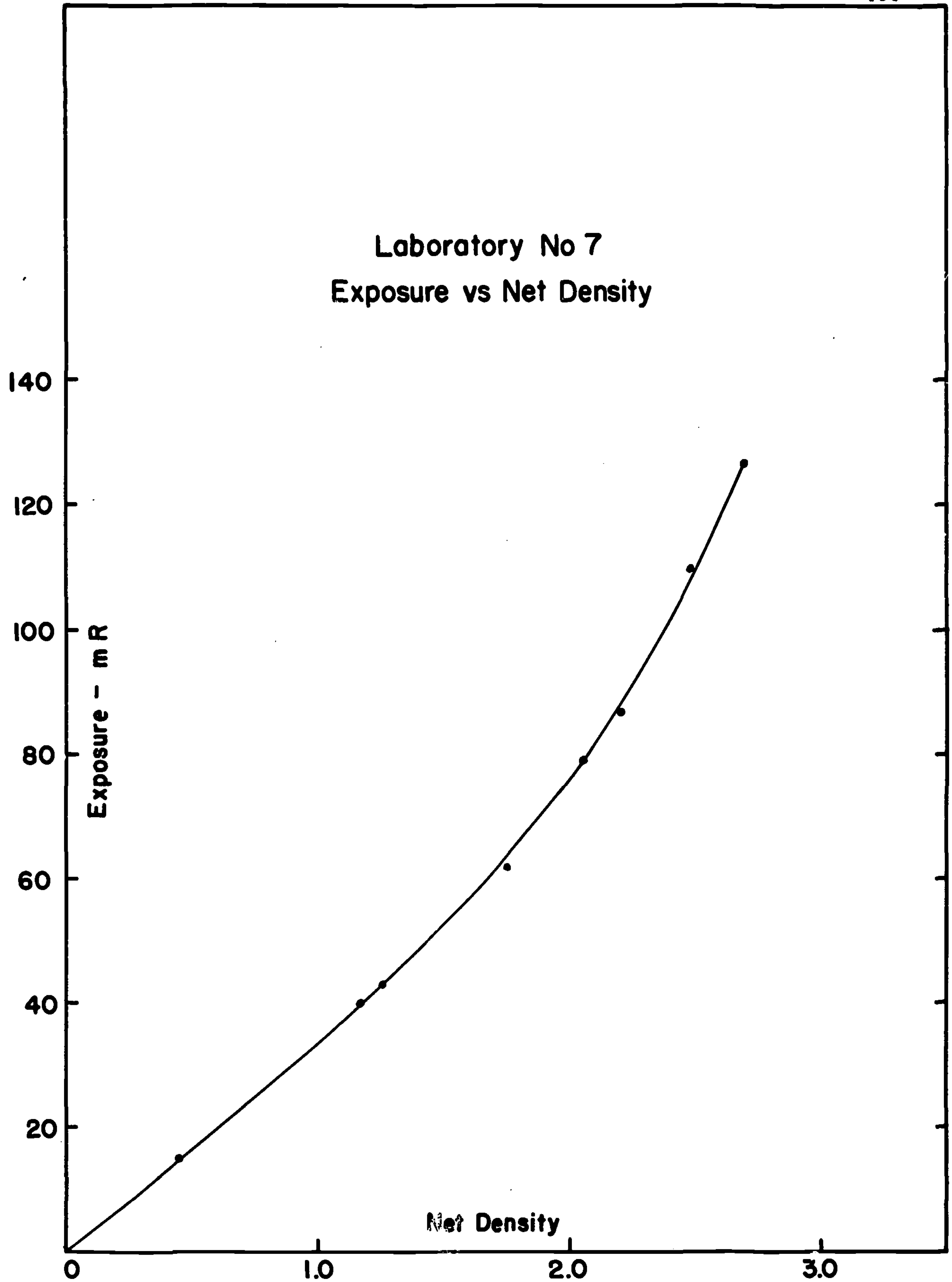
G. Plot net density vs exposure on linear graph paper.

H. Determine the exposure of the unknowns from the calibration graph.

Laboratory No. 7

TYPICAL DATA

Film No.	kVp	Added mmAl	Exposure-mR	Density Gross	Density Net	Estimated Exposure-mR
1	60	3mmAl	15	0.76	0.45	--
2	60	3mmAl	40	1.47	1.16	--
3	60	3mmAl	43	1.57	1.26	--
4	60	3mmAl	62	2.06	1.75	--
5	60	3mmAl	79	2.36	2.05	--
6	60	3mmAl	87	2.51	2.20	--
7	60	3mmAl	110	2.79	2.48	--
8	60	3mmAl	127	3.00	2.69	--
9	60	3mmAl	0	0.31	0	--
Unknowns						
10	60	3mmAl	12	0.68	0.37	12
11	60	3mmAl	99	2.74	2.43	105
12	50	0	105	2.68	2.37	100
13	100	3 mmAl	107	2.87	2.56	115
14	radium	gamma	215	0.91	0.60	20


Laboratory No 7
Exposure vs Net Density
140
120
100
80
60
40
20
Exposure - mR
Net Density
0
1.0
2.0
3.0

LABORATORY NO. 8

TITLE: Demonstration of the Effect of X-Ray Machine Factors on the X-Ray Spectrum

PURPOSE: To investigate the effects of kVp, filtration, and mA on the x-ray spectrum.

TIME: Three hours

MATERIALS FOR EACH STUDENT GROUP:

One Nuclear Data 512 Channel Analyzer (Model ND 130 A)

One Harshaw 1.5" x 1/4" NaI (Tl) crystal and photomultiplier tube assembly with 0.005" Be window

One 0.5 mm diameter collimator

One General Electric 90 kVp mobile x-ray machine

Three sheets linear graph paper, K & E 46-0703 or equivalent

One shipps curve, K & E 1685-48 or equivalent

REFERENCES:

Attix, Roesch, Tochilin
Radiation Dosimetry

Hine and Brownell
Radiation Dosimetry

Operating Instructions for Multichannel Analyzer

Trout, Kelley, Lucas
Influence of Cable Length on Dose Rate and Half-Value Layer in Diagnostic X-Ray Procedures

Laboratory No. 8

DEMONSTRATION OF THE EFFECT OF MACHINE FACTORS ON THE X-RAY SPECTRUM

I. PURPOSE

To investigate the effects of kVp, filtration, and mA on the x-ray spectrum.

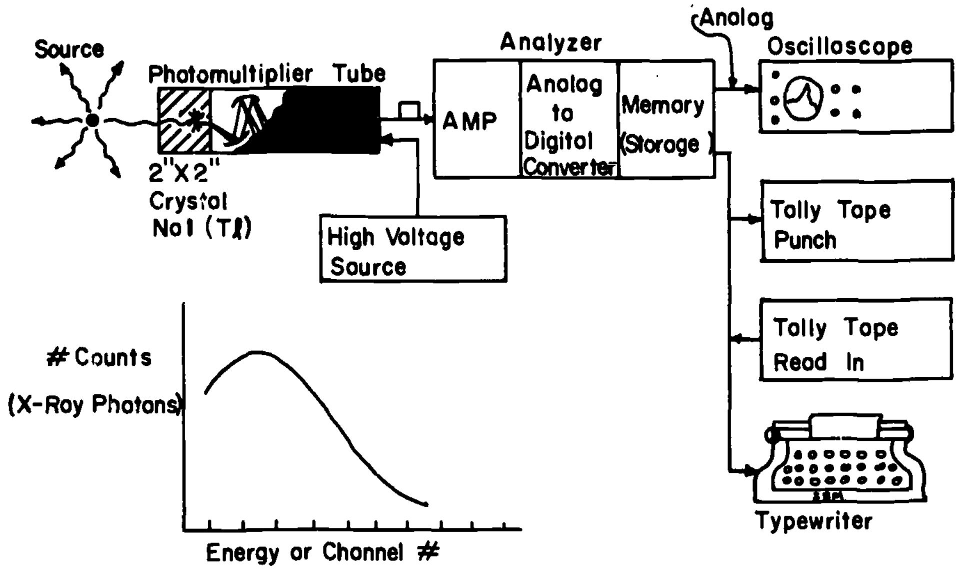
II. THE GAMMA-RAY SPECTROMETER

A. General Description

The gamma-ray spectrometer, pictured schematically below in Figure 1, consists of detection device (in this case a sodium-iodide crystal and photomultiplier), a high voltage power supply, and a pulse-height analyzer.

The detector is irradiated with x- or gamma radiation which it "shifts" to lower (light) frequencies. The intensity of the light flash emitted is proportional to the energy of the incident radiation. This light falls on the photocathode of the photomultiplier tube and electrons are emitted. The accelerated electrons, which yield an amplification of about 10^6, are collected at the last dynode and are sent to the pulse-height analyzer.

The signal from the detector's photomultiplier tube is received at the analyzer by the analog-to-digital converter (A.D.C.) which sorts the pulses as to their voltage and sends them to a memory unit. There, pulses of a given energy range are added until a readout (and counting stop) is desired. The memory can then be displayed on a cathode-ray tube, typeout, tape punch, or magnetic tape.



B. The Crystal

Photons interact in the crystal mainly by Compton scattering and photoelectric effect. In the photoelectric effect a photon enters the crystal, strikes an electron, and removes it from the atom (giving all its energy to the electron). The electron will in turn deposit all of its energy in the crystal, as the crystal is dense and will not allow the electron to escape. All the photon's energy will therefore be seen as a light flash. In Compton scattering, the photon only gives part of its energy to the electron. Therefore, if the photon interacts with the crystal by Compton scattering, there is a good chance, in a small crystal, that the photon will escape after depositing only part of its energy in the crystal. Ways of combating photon losses from Compton interactions include using larger crystals and irradiating only the center portion of the crystal.

In both cases, the electron ejected by the photon excites other atoms, whose excited electrons fall back to the ground state immediately. This falling results in a brief light flash, which would be absorbed by the crystal if it were not for the trace impurity of Thallium (Tl), which does not absorb the light and lets it pass to the light pipes.

Light pipes are used so there is a minimum loss of light between the crystal surface and the photomultiplier surface.

C. The Analyzer

The controls on the analyzer which are important in this lab are explained below:

1. Number of Channels to be Analyzed

   Located on the far left-hand side of the analyzer, choose one of the switches. This also picks the number of channels to be read out. With this, the channels may be grouped into as many as four groups.

2. Sub-Group
   a. Second column from left
   b. Pick one to number of channels desired

3. Readout-Analyze Switch
   a. Readout is far right, analyze on far left
   b. Stop One--stops all readout and analyzing, and returns the machine to channel number one
   c. Stop Two--does not stop readout, and does not return the readout to the first channel

4. Erase Switch Section
   a. ALL erases everything showing on the C.R.T.
   b. LEFT erases left portion of the spectrum
   c. SUM erases integrated sum

5. Readout Mode--Switch Section
   a. Located directly below erase switch

b. Readouts are ANALOG and DIGITAL

(1.) TAPE, TYPE, and MAGNETIC TAPE on digital

(2.) C.R.T. and PEN on analog

c. THE READOUTS ARE COLOR CODED. A GREEN function goes with a GREEN mode.

d. To punch out, the PUNCH button on the TAPE control (Located on the INTEGRATE section of the analyzer) must be UP.

6. Live Timer Switch

a. This should be left ON, since the machine momentarily does not accept pulses while the A.D.C. is sorting a pulse previously accepted. With this switch on, the machine counts all activities for the same amount of elapsed counting time.

b. The DEAD TIME meter indicates the time the machine is sorting an accepted pulse and getting ready to accept another. Samples exceeding 90% dead time are worthless analytically.

7. Time Selector

a. Located directly below the live timer switch. This controls the amount of time to be counted.

b. A source can be counted for as long as 800 minutes or as short as 1 minute.

c. If the machine is analyzing and a check of the analysis is desired, it is possible to check by going to readout and back to analyze WITHOUT ERASING (erase buttons below the readout switch). The remaining time from the original time setting will be used, and a readout produced at the end of the time.

d. If the readout shows that starting over is desired, simply ERASING will erase both the time left and the original sample, and a new time may start.

8. Group Interchange

Changes memory from one side to another.

9. Overlap

a. This will allow the operator to place one spectrum from one side on another.

b. Leave this off when analyzing

10. Computer Initiate Button

Allows background radiation samples to be subtracted and integrations to be made.

11. Gain Control

Increasing gain shifts the whole spectrum up and conversely.

12. Zero Energy Control

Increasing this moves the ends of the spectrum further apart.

13. Integration

a. An entire spectrum can be integrated by putting the INTEGRATION switch to ALL, placing the ADD-SUBTRACT switch to ADD, and COMPUTER INITIATE to 1, and initiating the cycle once.

b. Portions may be integrated by going to SELECT and choosing the proper number of channels.

14. Subtraction

a. Subtracting one spectrum from another is accomplished by first placing both spectrums on the C.R.T.

The one to be subtracted is on the right-hand side (Adjust by group interchange).

b. Place the ADD-SUBTRACT switch to SUBTRACT.

c. Place COMPUTER MULTIPLIER to appropriate multiplier and initiate.

d. OVERLAP and INTEGRATION must be OFF!

III. PROCEDURE

Prior to each of the following, the spectrometer calibration should be adjusted to provide 1 keV per channel and the 1/2 mm diameter collimator placed in the detector entry port.

A. Effect of Tube Current on Spectrum

1. Operate x-ray machine at 60 kVp, 1 mA with 1 mm Al added filtration.

2. Collect spectrum data for 1 minute (live time) in 1st quarter of analyzer memory.

3. Have students observe spectrum on C.R.T. and print-out data on IBM typewriter (provide enough carbon copies for one per two students).

4. Integrate spectrum from channels 6 through 64.

5. Adjust tube current to 2 mA holding kVp at 60.

6. Repeat step B above using 2nd quarter of memory.

7. Allow students to compare both spectra by means of the spectrometer overlap function.

8. Print-cut data.

9. Have students plot data superimposing both spectra on same sheet of graph paper. (Plotting every 5th channel is sufficient.)

B. Effect of Kilovoltage on Spectrum

1. Operate x-ray machine at 1 mA and 50 kVp with no added filtration.

2. Collect spectrum data for 1 minute in 1st quarter of analyzer memory.

3. Print-out data.

4. Have students plot data.

5. Repeat steps B through D for 60, 70, 80, and 90 kVp, in each case holding the mA constant at 1 mA. Data should be plotted on the same sheet of graph paper superimposing spectra.

C. Effect of Filtration on Spectrum

1. Operate x-ray machine at 80 kVp, 1 mA with no added filtration.

2. Collect spectrum data for 1 minute in 1st quarter of analyzer memory.

3. Print-out data.

4. Have students plot data.

5. Repeat steps B through D for 1/4 mm, 1/2 mm, 1 mm, 2 mm, and 3 mm of Al added filtration in each case holding constant at 80 kVp and 1 mA. Data should be plotted on the same sheet of graph paper superimposing spectra.

LAB NO. 8

I. EFFECT OF MILLIAMPERAGE UPON SPECTRUM

60 kVp 1 mA 1 mm Al added filtration 1 min. live time

0000004277

010000	005414	003456	001337	000490	000243	000230	000264
000403	000636	001010	001510	002060	002636	003175	003442
003569	003269	002915	002514	001951	001574	001274	001034
000951	000867	000693	000710	000541	000492	000407	000342
000267	000235	000141	000115	000080	000044	000035	000041
000023	000022	000010	000010	000007	000001	000007	000005
000003	000002	000002	000003	000002	000002	000002	000000
000000	000001	000001	000004	000001	000001	000001	000006

60 kVp 2 mA 1 mm Al 1 min. live time

010000	005675	003653	001546	000634	000433	000409	000514
000750	001168	001796	002700	003848	004940	005884	006442
006680	006331	005672	004748	003743	003001	002441	002033
001779	001547	001431	001236	001143	001009	000807	000720
000601	000476	000335	000258	000197	000140	000107	000086
000040	000040	000039	000020	000021	000015	000011	000008
000013	000012	000006	000008	000007	000009	000005	000002
000007	000005	000004	000003	000007	000005	000002	000003
000000	000002	0000					

II. EFFECT OF KILOVOLTAGE ON SPECTRUM

50 kVp 1 mA No added filtration

010000	005321	003543	001259	000407	000193	000173	000268
000454	000718	001144	001548	002039	002472	002654	002751
002925	002483	002010	001682	001325	000912	000631	000414
000320	000179	000132	000089	000060	000043	000026	000019
000017	000008	000012	000010	000004	000002	000000	000003
000004	000000	000005	000002	000001	000005	000001	000005
000003	000002	000000	000003	000002	000001	000005	000004

60 kVp lmA No added filtration

010000	005708	003707	001355	000538	000339	000350	000464
000796	001136	001828	002550	003207	004125	004602	005060
005058	004764	004176	003448	002694	002121	001645	001368
001146	000978	000821	000747	000641	000589	000513	000428
000328	000285	000176	000113	000112	000064	000060	000031
000025	000019	000017	000012	000007	000007	000003	000005
000004	000004	000002	000004	000000	000005	000002	000003
000003	000000	000003	000002	000004	000002	000003	000001

70 kVp lmA No added filtration

010000	006409	003880	001514	000652	000438	000497	000644
000992	001467	002196	003115	004259	005373	006285	006783
006967	006441	005664	004900	003895	003185	002613	002133
001871	001782	001786	001638	001594	001566	001471	001398
001201	001109	000921	000819	000678	000539	000461	000277
000247	000180	000136	000088	000086	000052	000037	000043
000040	000017	000017	000011	000013	000003	000011	000008
000011	000010	000007	000005	000004	000005	000007	000004
000005	000003	000004	000002	000001	000002	000003	000004

80 kVp lmA No added filtration

010000	006944	004045	001708	000766	000544	000666	000781
001138	001701	002577	003593	004985	006282	007470	008085
008424	007865	007277	005847	004988	003915	003310	002805
002464	002371	002347	002374	002500	002502	002394	002335
002313	002138	001954	001809	001674	001462	001216	001062
000947	000780	000618	000468	000393	000276	000197	000164
000138	000097	000100	000057	000053	000037	000048	000029
000025	000029	000016	000027	000019	000016	000018	000015
000013	000011	000009	000012	000003	000014	000008	000008
000007	000006	000003	000004	000002	000003	000002	000003

90 kVp 1MA No added filtration

010000	009974	004418	001871	000858	000607	000650	000814
001290	001819	002765	003925	005409	006912	008174	009237
009462	009185	008374	007078	006032	004913	003880	003329
003178	003085	003116	003131	003291	003345	003342	003424
003394	003372	003323	003215	003000	002822	002765	002397
002083	001908	001703	001427	001317	001158	000954	000752
000632	000552	000371	000312	000235	000211	000187	000147
000124	000110	000075	000071	000069	000060	000051	000045
000041	000039	000039	000038	000044	000026	000036	000021
000027	000022	000020	000013	000019	000011	000019	000013
000019	000008	000008	000012	000004	000006	000006	000008
000010	000006	000005	000001	000008	000008	000004	000002

III. EFFECT OF FILTRATION SPECTRUM

80 kVp lmA No added filtration

010000	007075	004094	001620	000682	000404	000444	000586
000886	001307	001939	002739	003899	004823	005785	006400
006642	006333	005559	004653	003817	003169	002583	002223
001972	001899	001915	001980	001980	002000	001993	001920
001907	001851	001673	001496	001487	001249	001062	000908
000786	000626	000547	000389	000316	000238	000201	000134
000106	000080	000047	000039	000038	000023	000017	000025
000020	000023	000008	000016	000008	000012	000012	000014
000012	000009	000006	000009	000010	000007	000005	000003
000005	000004	000005	000004	000003	000004	000004	000003
000002	000004	000003	000005	000007	000002	000002	000001
000005	000002	000002	000002	000002	000004	000002	000005

80 kVp lmA 1/4 mm added filtration

010000	007585	004092	001583	000651	000401	000404	000463
000714	001103	001574	002320	003300	004090	004972	005664
005876	005772	005111	004350	003566	002864	002394	002032
001995	001825	001919	001909	001888	001922	001950	001849
001766	001803	001639	001522	001416	001252	001057	000908
000808	000617	000533	000390	000343	000236	000185	000140
000120	000077	000069	000041	000038	000032	000022	000020
000010	000011	000013	000010	000013	000015	000011	000008
000011	000005	000012	000011	000008	000004	000007	000005
000006	000008	000006	000005	000007	000003	000003	000004
00							

80 kVp lmA 1/2 mm added filtration

510000	006929	004955	001734	000648	000381	000412	000527
000656	000980	001409	002151	002923	003936	004855	005416
005563	005445	004893	004201	003528	002842	002372	002054
001825	001880	001932	001897	001977	002077	001933	002002
001942	001800	001727	001597	001458	001314	001167	000952
000851	000668	000550	000432	000343	000297	000213	000176
000091	000095	000077	000050	000035	000034	000026	000019
000015	000024	000015	000011	000012	000019	000014	000011
000012	000007	000008	000006	000003	000009	000002	000003
000003	000008	000002	000005	000007	000005	000004	000001
0							

80 kVp   1mA   1 mm Al added filtration

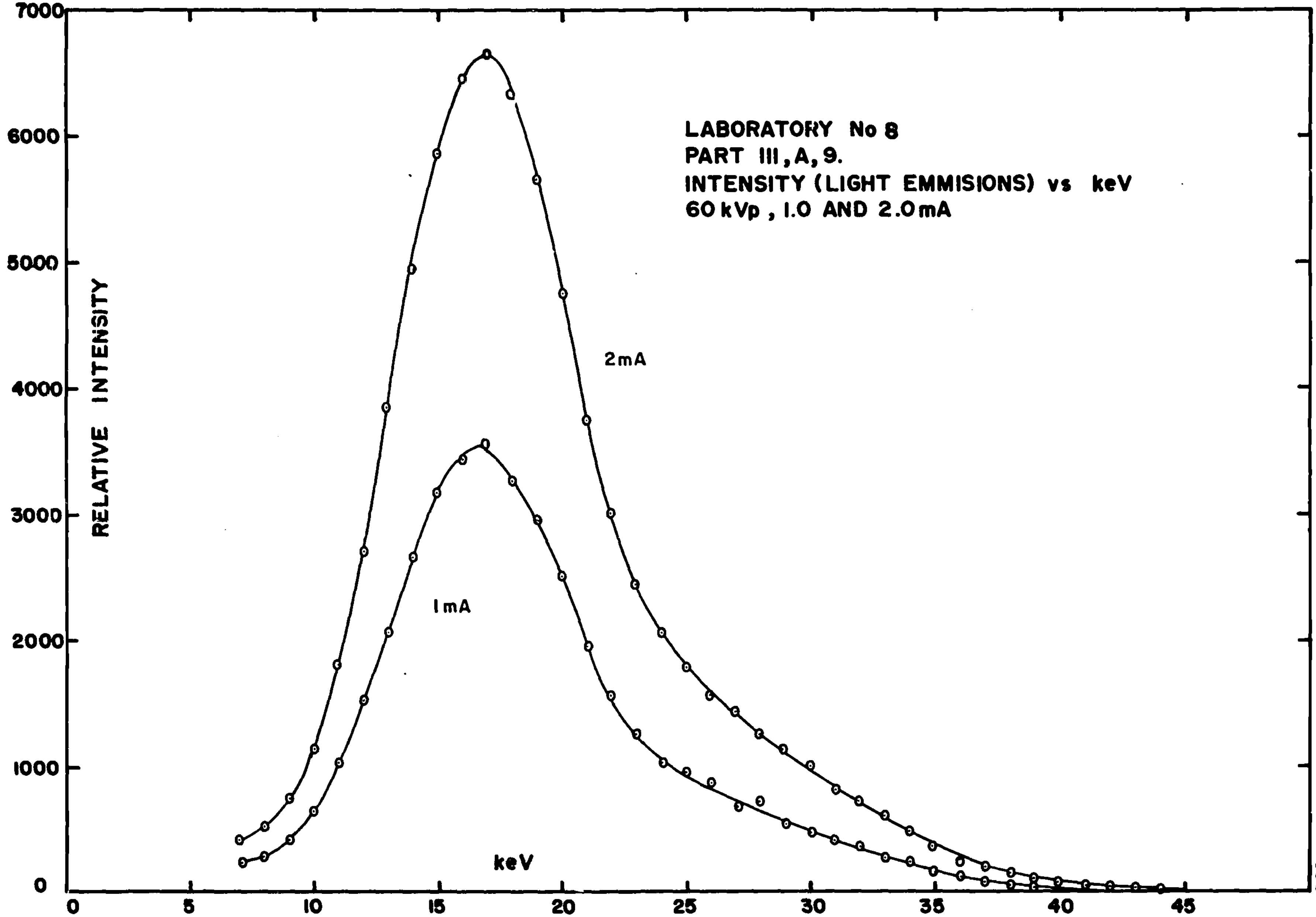
010000	006789	004141	001528	000649	000382	000348	000468
000560	000758	001238	001809	002545	003355	004290	004777
005097	004854	004561	003868	003148	002621	002242	001931
001806	001776	001689	001813	001851	001824	001822	001861
001837	001700	001560	001484	001333	001207	001074	000920
000793	000625	000510	000404	000330	000276	000173	000145
000096	000077	000063	000048	000031	000025	000023	000019
000018	000015	000018	000008	000010	000009	000008	000007
000010	000007	000004	000005	000006	000007	000003	000007

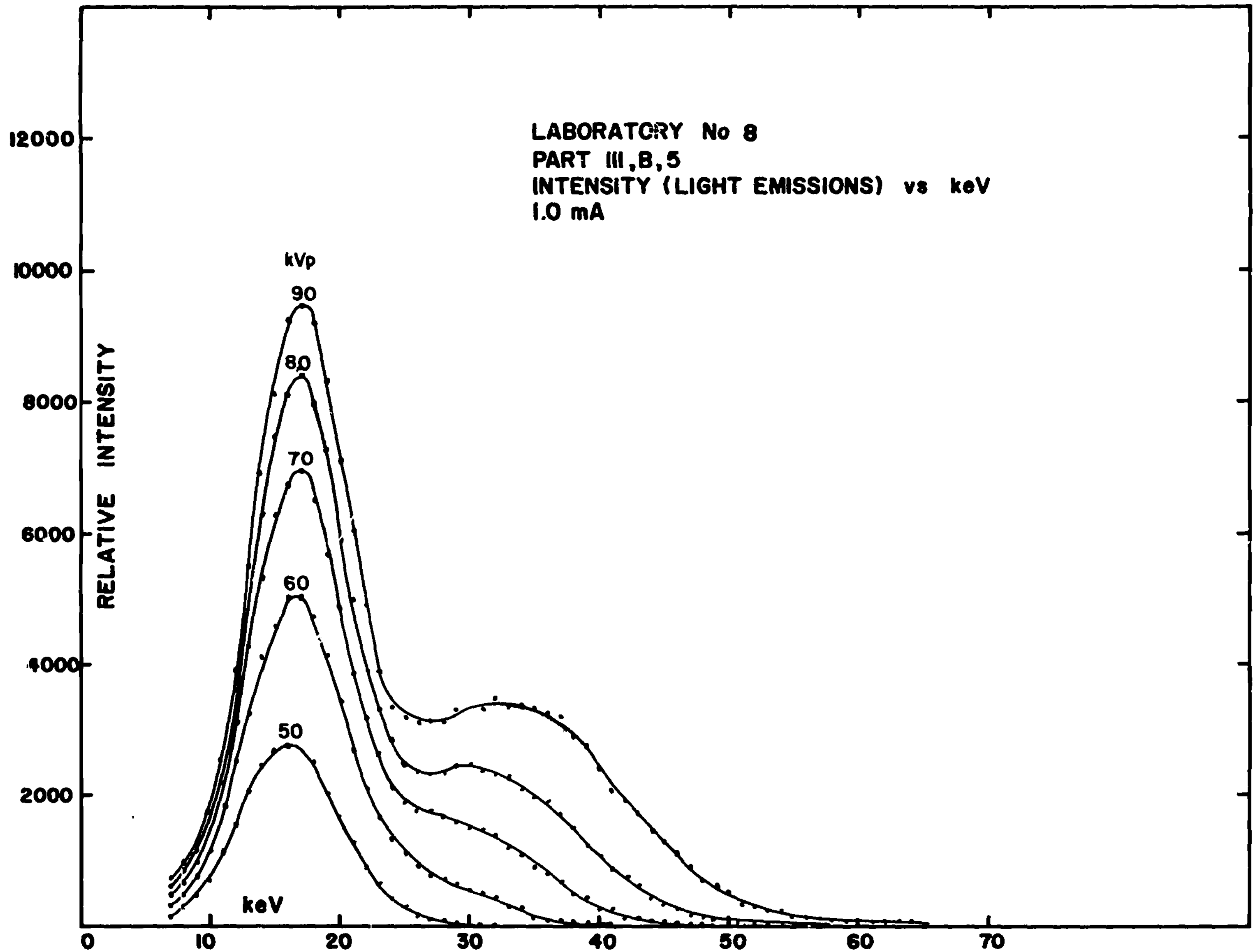
80 kVp   1mA   2 mm Al added filtration

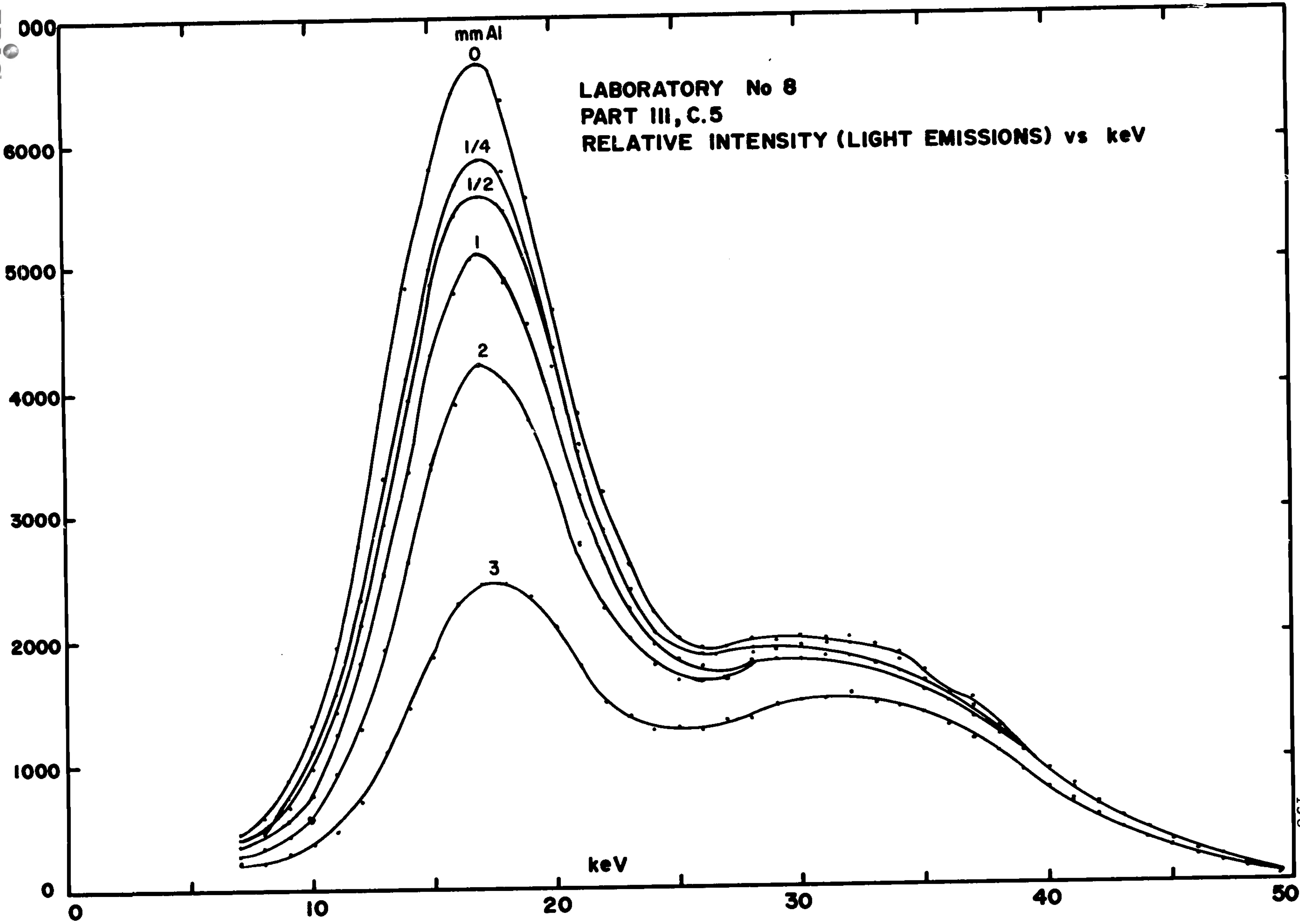
010000	007095	004063	001446	000615	000307	000297	000345
000433	000567	000933	001294	001941	002653	003404	003895
004210	004071	003752	003247	002768	002239	002009	001792
001658	001678	001647	001785	001793	001916	001876	001864
001818	001753	001636	001483	001404	001221	001085	000935
000876	000660	000581	000449	000377	000261	000166	000131
000118	000085	000054	000030	000029	000026	000026	000016
000015	000011	000010	000008	000010	000018	000008	000008
000011	000015	000006	000007	000004	000006	000006	000005

80 kVp   1mA   3 mm Al added filtration

010000	006488	003955	001457	000544	000237	000233	000233
000297	000380	000478	000700	001105	001466	001862	002300
002465	002450	002337	002105	001782	001476	001387	001267
001283	001260	001329	001359	001440	001479	001490	001536
001465	001445	001379	001288	001192	001058	000911	000777
000698	000549	000456	000362	000309	000200	000186	000116
000090	000061	000051	000032	000023	000019	000017	000011
000010	000010	000014	000006	000004	000004	000008	000011
000006	000003	000010	000001	000006	000007	000004	000005
000004	000005	000005	000002	000005	000004	000004	000003
000006	000004	000003	000005	000002	000005	000005	000002


LABORATORY No 8
PART III, A, 9.
INTENSITY (LIGHT EMMISIONS) vs keV
60 kVp, 1.0 AND 2.0 mA
2 mA
1 mA
RELATIVE INTENSITY
keV
0
1000
2000
3000
4000
5000
6000
7000
0
5
10
15
20
25
30
35
40
45


LABORATORY No 8
PART III,B,5
INTENSITY (LIGHT EMISSIONS) vs keV
1.0 mA
RELATIVE INTENSITY
keV
kVp
90
80
70
60
50
12000
10000
8000
6000
4000
2000
0
10
20
30
40
50
60
70


LABORATORY No 8
PART III, C.5
RELATIVE INTENSITY (LIGHT EMISSIONS) vs keV
mm Al
0
1/4
1/2
1
2
3
keV
0
1000
2000
3000
4000
5000
6000
000
0
10
20
30
40
50

GS-462

Test No. 1

Part I. Multiple choice. Circle the letter preceding the answer which correctly completes the statement. Grade value 4 points each.

1. The fundamental mechanism upon which radiation measuring instruments utilizing gas-filled chambers rely is:
   a. photomultiplication
   b. ionization
   c. recombination
   d. continuous discharge
   e. excitation

2. Quality factor (QF):
   a. relates exposure to absorbed dose
   b. multiplied by exposure in roentgens yields dose in rem
   c. depends only on radiation energy
   d. is used exclusively in radiation biology
   e. is used to derive the dose equivalent

3. The rad:
   a. applies only to x and/or gamma radiation
   b. is the special unit of dose equivalent
   c. is equivalent to 100 ergs/g
   d. applies to energy imparted only to air
   e. all of the above

4. The roentgen:
   a. is the special unit of exposure
   b. applies only to electromagnetic ionizing radiation
   c. applies only to interactions in air
   d. is equivalent to 2.58×10^{-4} C/kg air
   e. all of the above

5. The half-value layer for a 70 keV beam of photons is approximately 1.2 cm of aluminum. The thickness of aluminum that will reduce the beam intensity to 3.125% (1/32) of its original intensity is:

   a. 6.0 cm
   b. 5.5 cm
   c. 5.0 cm
   d. 4.0 cm
   e. 3.0 cm

6. The half-value layer (HVL) of an x-ray beam is not influenced by:

   a. kVp
   b. mA
   c. filtration
   d. measuring geometry
   e. none of the above

7. The homogeneity coefficient:

   a. is the ratio of the second HVL to the first HVL
   b. increases as mA increases
   c. is always greater than 1
   d. decreases as added filtration increases
   e. decreases as kVp increases

8. The x-ray beam field distribution from a reflection target x-ray tube is influenced by:

   a. the inverse-square law
   b. the "heel effect"
   c. the x-ray tube target angle
   d. the peak kilovoltage
   e. all of the above

9. In attenuation of a photon beam in matter by the photoelectric effect:

   a. only free or loosely bound electrons are involved

   b. a photon gives up all of its energy in a single interaction

   c. the photons give up only part of their energy in a single interaction

   d. the fractional attenuation is directly proportional to the photon energy

   e. all of the photon energy is transferred to the kenetic energy of the ejected electron

10. In a gas filled chamber used to detect radiation, the ionization current is:

    a. directly proportional to the incident x-ray intensity

    b. inversely proportional to the incident x-ray intensity

    c. independent of x-ray intensity

    d. read using a 0 - 5 ampere d.c. meter

    e. none of the above

Part II. True-false. Grade value 3 points each.

F 1. The roentgen is defined for any x-ray or gamma ray energy.

T 2. To a good approximation ($\pm$ 20%) exposure = absorbed dose = dose equivalent for x-rays interacting with tissue.

T 3. The interaction mechanism of primary importance for luminescent radiation detecting media is excitation.

F 4. A 100 kVp x-ray beam will always have a greater homogeneity coefficient than a 75 kVp x-ray beam.

F 5. The "heel effect" would be more pronounced with a 22 1/2^{o} target angle tube than with a 12 1/2^{o} target angle tube.

T 6. With a source-filter distance equal to 1/2 of the source-chamber distance, all other factors constant, as the source-chamber distance is increased the half-value layer decreases.

T 7. The greater the amount of scattered radiation to the measuring chamber, the greater will be the measured half-value layer.

Part III. Grade value of each question shown in parenthesis.

1. Define the following:

(4) a. Directly ionizing particles

Ans. Charged particles that produce ionization directly or through interaction with atoms of material exposed

(4) b. Indirectly ionizing particles

Ans. Uncharged particles that can liberate directly ionizing particles by collision

(4) c. Rem

Ans. Unit of dose equivalent

(4) d. Dose equivalent

Ans. DE = (D) (QF) (DF) - - - dose in rads times quality factor times distribution factor times any other modifying factors

(4) 3. Exposure

Ans. $X = \frac{\Delta Q}{\Delta m}$ ΔQ sum if all charges liberated in air of mass Δm where all electrons are completely stopped in air

2. The transmission curves in Figure 1 were taken with aluminum absorbers in the useful beam of an x-ray machine. One or more of the machine factors (kVp, mA, filtration) was changed from condition A to condition B. SHOW ALL WORK in answering the following:

(5) a. Determine the first half-value layer for A and B.

Ans. A HVL = 0.9 mmAl

B HVL = 0.9 mmAl

(6) b. Determine the homogeneity coefficient for A and B.

Ans. A 2HVL = 2.37 - 0.9 = 1.47

B 2HVL = 2.58 - 0.9 = 1.68

A $H = \frac{0.90}{1.47} = 0.613$ B $H = \frac{0.90}{1.68} = 0.536$

(5) c. What is the effective energy of each beam? (See Figure 2)

Ans. $\mu/\rho = \frac{0.693}{(HVL)}$ $A = B = \frac{0.693}{(0.09)(2.7)} = 2.85 \rightarrow 21.3$ keV

(6) d. What change(s) in machine factor(s) account for the difference in data sets A and B? For each factor (kVp, mA, filtration) indicate which data set, A or B, has the larger value.

Ans. kVp A < B
Filter A < B
mA A < B

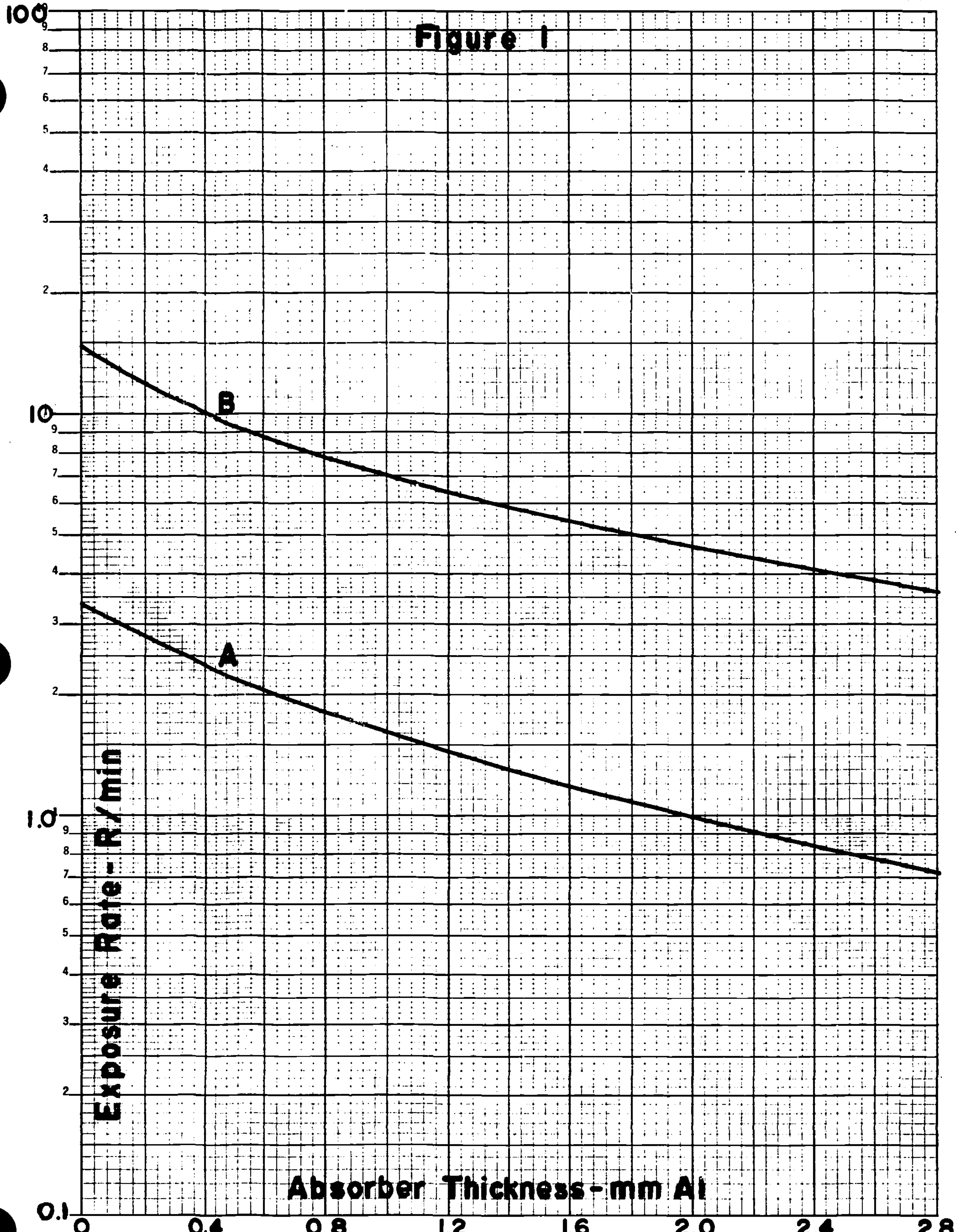


Figure 1
100
10
1.0
0.1
B
A
Exposure Rate - R/min
Absorber Thickness - mm Al
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8

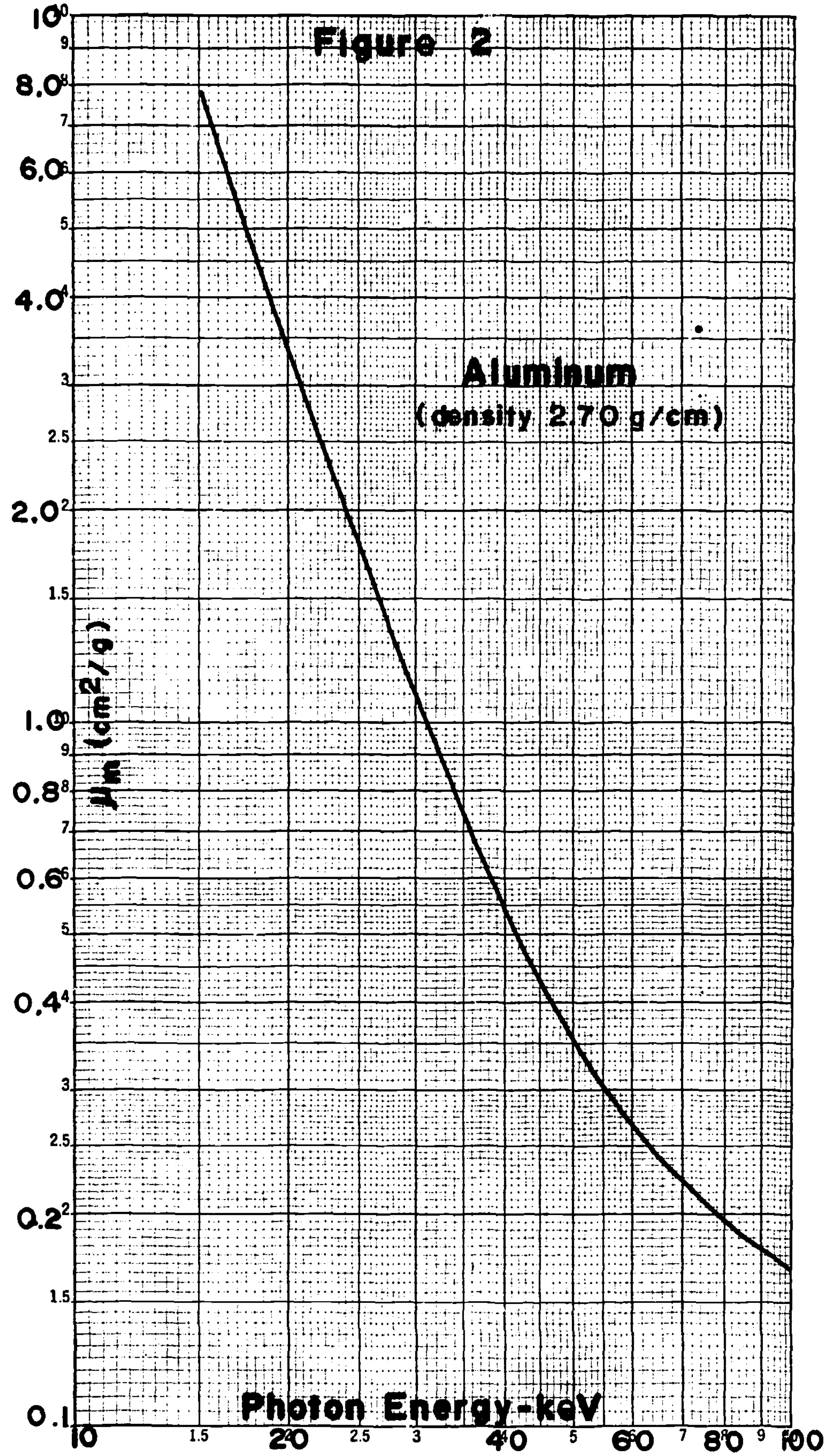


Figure 2
Aluminum
(density 2.70 g/cm)
μ_m (cm^2/g)
Photon Energy-keV
10
8.0
6.0
4.0
2.0
1.0
0.8
0.6
0.4
0.2
0.1
10
20
40
60
80
100

GS-462 X-RAY MEASUREMENT

SECTION III

EXAMINATIONS

Name ____________________

GS 462

Test No. 2

Part I. Multiple choice. Circle the letter preceding the answer which correctly completes or answers the statement. Grade value 4 points each.

1. For a given volume and configuration of a gas filled chamber used to detect radiation, the "region" (recombination, ionization chamber, etc.) of operation is determined by:
   a. the source of the initial interaction (alpha, beta, gamma, x ray, etc.)
   b. the material in the chamber wall.
   c. the energy of the radiation.
   d. the voltage at which the chamber is operated.
   e. the intensity of the radiation being detected.
2. If a survey meter is exposed to a beam of x rays for a length of time equal to the RC time constant of the instrument and reads 100 mR/h, approximately what would be the meter reading if exposed to the x-ray beam 6 times as long as the RC time constant
   a. 100 mR/h
   b. 160 mR/h

c. 300 mR/h

d. 480 mR/h

e. 600 mR/h

3. A current of 10^{-10} ampere is read using an ionization chamber with a volume of $1\ cm^3$. What is the exposure rate in mR/minute. Assume STP and 1 coulomb = 3×10^9 esu.

   a. 18000 mR/min

   b. 6000 mR/min

   c. 1800 mR/min

   d. 600 mR/min

   e. 180 mR/min

4. Which of the following x-ray detection methods is most widely used in x ray survey instruments

   a. gas

   b. scintillation

   c. thermoluminiscent

   d. chemical

   e. photographic emulsions

5. The half-value layer for a 50keV beam of photons is approximately 0.8 cm of aluminum. The thickness of aluminum that will reduce the beam intensity of 6.25% (1/16) of its original intensity is:

   a. 6.0 cm

b. 4.8 cm

c. 4.0 cm

d. 3.2 cm

e. 2.4 cm

6. The homogeneity coefficient:

a. is the ratio of the second HVL to the first HVL.

b. increases as kVp increases.

c. decreases as added filtration increases.

d. decreases as source-chamber distance increases.

e. decreases as tube current increases.

7. The x-ray beam field distribution <u>is not</u> influenced by:

a. the x-ray tube potential

b. the x-ray tube current

c. the "heel effect"

d. the x-ray tube target angle

e. the added filtration

8. The half-value layer of an x-ray beam is influenced by:

a. the size of the measuring chamber

b. the length (exposure time) of the x-ray exposures

c. the barometric pressure

d. the temperature of the air in the measuring chamber

e. the location of the added filters

9. A survey meter designed for x ray use from 100 - 1000 keV and used to measure the leakage radiation from a 25 keV x-ray source will likely have a correction factor:

   a. greater than 1.00
   b. less than 1.00
   c. equal to 1.00
   d. independent of photon energy
   e. none of the above

10. The time response of an ionization chamber type survey meter used to measure an x-ray beam <u>is</u> <u>not</u> influenced by:

    a. the RC time constant
    b. the inertia of the meter movement
    c. the incident x-ray photon energy
    d. the range selector resistance
    e. the circuit capacitance

Part II. True - False. Grade value 3 points each.

__F__ 1. The interaction mechanism of primary importance for air chamber detecting media is excitation.

__F__ 2. A 100 kVp x-ray beam will never have a homogeneity coefficient less than 0.5.

__F__ 3. The rad is defined only for x rays or gamma rays interacting in air.

__F__ 4. The energy correction factor for a typical survey meter is never less than 1.0.

__F__ 5. The response of a chamber operating in the proportional chamber region is independent of chamber voltage.

__T__ 6. The response of a chamber operating in the ionization chamber region is independent of chamber voltage.

__F__ 7. The response of a chamber operating in the recombination region is independent of chamber voltage.

__F__ 8. The operating region of primary importance for x-ray survey instruments is the Geiger region.

__F__ 9. The ionization chambers used in survey meters are always sealed.

__T__10. For a gas amplification factor of 1.0, the number of ions collected equals the number of ions initially produced.

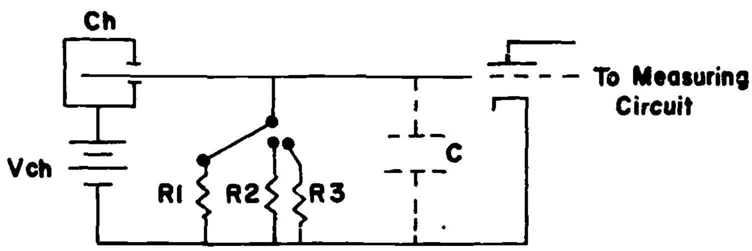
Part III. Grade value 10 points each.

1. List and briefly describe the types of ion recombination that can occur in an ionization chamber.

   Ans. 1. Initial - occurs at or very near location of ion production

   2. General - occurs other than at locations of ion production. Function of chamber voltage

2. Sketch the circuit diagram of the ionization chamber portion of a typical DC amplifier survey meter. Label the component parts. (chamber, range selector, etc.)



3. A Victoreen R-meter has a fully-charged voltage of 500 volts and is used with a 25 R chamber. The chamber/electrometer sensitivity (S) is 10 V/R. If the chamber capacitance is 50 pF, calculate the capacitance of the electrometer, the sensitivity of the chamber and the effective air volume of the

chamber. Note: when the fully charged chamber was inserted in a completely discharged electrometer, the scale reading was 10.0 R. Also $Q = CV$, $\frac{V_t}{V_m} = \frac{C + C_e}{C}$, and $v = \frac{V}{R} (3 \times 10^9 C)$

Ans. Scale reading of 10 R corresponds to a voltage drop of (10 V/R) (10R) = 100 volts and a final voltage of 500 - 100 = 400 volts. This loss of charge Q = CV = (50 pF) (100V) charged the electrometer to 400 volts

$$\text{so } C_e = C \frac{V_{drop}}{V_{rad}} = (50) \frac{100}{400} = 12.5 \text{ pF}$$

$$\frac{V_t}{V_m} = \frac{C + C_e}{C} = \frac{50 + 12.5}{50} = \frac{62.5}{50} = 1.25$$

$$\text{so } V_t = 1.25\, V_m = (1.25)\ (100) = 125\text{V}$$

$$\text{so S of chamber} = \frac{125\text{V}}{10\text{R}} = 12.5 \text{ V/R}$$

$$v = \frac{V}{R} (3 \times 10^9 C), \quad \frac{V}{R} = S$$

$$v = (12.5)\ (3 \times 10^9)\ (50 \times 10^{-12}) = 1.875 \text{ cm}^3$$

Name ____________________

GS-462 X-Ray Measurement
1970-1971
Final Exam

Part I--Multiple choice. Circle the letter preceding the answer which correctly completes the statement or answers the question. Grade value 5 points each.

1. The density of an exposed film is determined to be 2.0. This corresponds to a light transmission of:

   a. 10^{2}
   b. 2^{10}
   c. 10^{-2}
   d. 2^{-10}
   e. 20

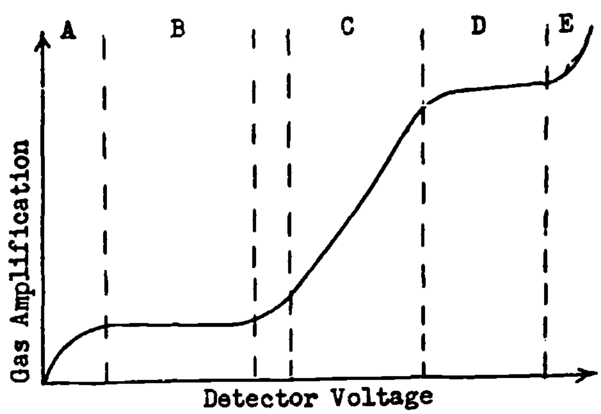


Figure 1

2. Figure 1 above shows gas amplification factor vs detector voltage for a gas filled detector. Which region is called the ionization chamber region?

   a. A
   b. B
   c. C
   d. D
   e. E

3. In Figure 1, which region is the Geiger-Mueller region?
   a. A
   b. B
   c. C
   d. D
   e. E
4. In Figure 1, which region is the proportional chamber region?
   a. A
   b. B
   c. C
   d. D
   e. E
5. Which of the following geometric variables must be considered when determining half-value layers?
   a. diameter of field at the added absorbers
   b. source-chamber distance
   c. source-absorber distance
   d. both a and c
   e. all of the above
6. Which of the following instruments would be best suited for making measurements to be used in determining the half-value layer of an x-ray beam?
   a. condenser R-meter
   b. proportional-type survey meter
   c. ionization chamber-type survey meter
   d. chemical dosimeter
   e. LiF thermoluminescent dosimeter

7. The response time of a survey meter is influenced by:

   a. the inertia of the meter movement

   b. photon energy

   c. the RC time constant

   d. both a and c

   e. all of the above

8. An individual who first begins working at a radiation facility at age 20 would be allowed to occupationally accumulate by age 25 a maximum whole body dose of:

   a. 25 rem

   b. 30 rem

   c. 35 rem

   d. 75 rem

   e. 125 rem

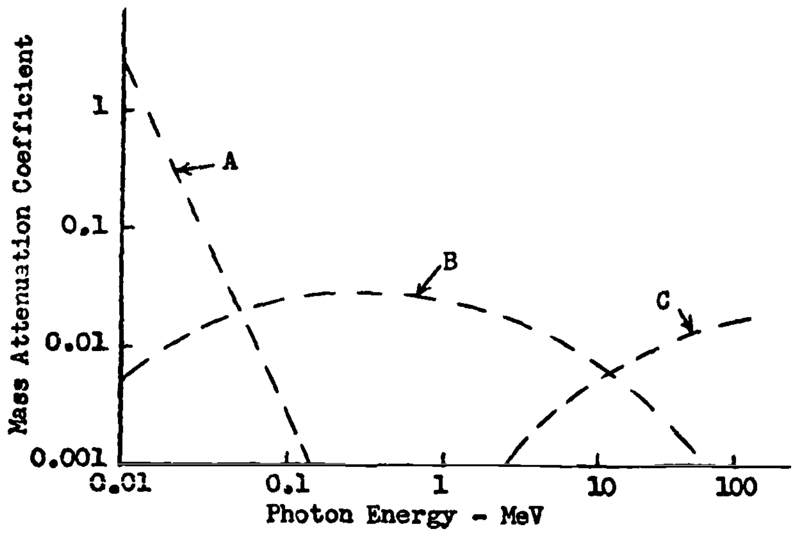


Figure 2

9. Figure 2 shows mass attenuation coefficient vs photon energy for water. Which curve represents the mass attenuation coefficient for the photoelectric effect?

   a. A
   b. B
   c. C

10. In Figure 2, which curve represents the mass attenuation coefficient for Compton scattering?

   a. A
   b. B
   c. C

11. In Figure 2, which curve represents the mass attenuation coefficient for pair production?

   a. A
   b. B
   c. C

12. The half-value layer of a 100 keV beam of photons is approximately 4 cm of water. The thickness of water that will reduce the beam intensity to 3.125% (1/32) of its original intensity is:

   a. 12 cm
   b. 16 cm
   c. 20 cm
   d. 24 cm
   e. 28 cm

Part II--Matching. In the blank space at the beginning of each of the following, write the letter corresponding to the correct term taken from the list that follows questions. Grade value 3 points each.

1. __j__ unit of dose equivalent
2. __b__ unit of exposure
3. __h__ unit of dose
4. __k__ indirectly ionizing radiation
5. __g__ one roentgen is equivalent to
6. __e__ one rad is equivalent to
7. __o__ the unique half-value layer is
8. __d__ absorbed dose in air
9. __n__ absorbed dose in medium other than air
10. __m__ maximum accumulated whole body dose equivalent

a. electrons

b. roentgen

c. dependent on geometry

d. 0.87X

e. 100 ergs/g

f. $e^{-\mu x}$

g. 2.58×10^{-4} coulomb/kg air

h. rad

i. 100 esu/g

j. rem

k. x rays

l. 100 ergs/cm^3

m. 5 (N-18) rem

n. $D_a \dfrac{(\mu_{en}/\rho)_m}{(\mu_{en}/\rho)_a}$

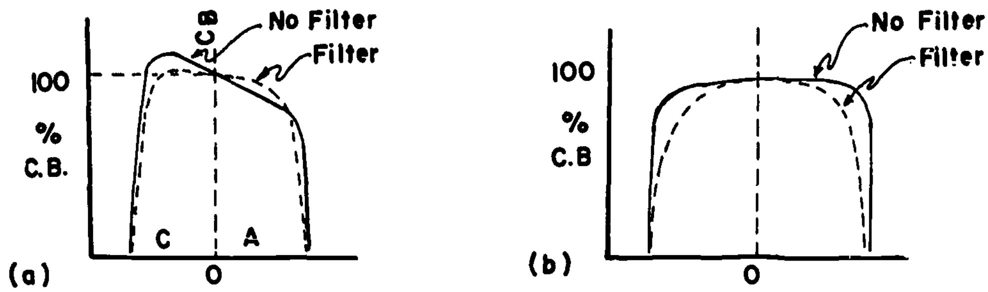
o. determined at zero field diameter

p. $\dfrac{\Delta V}{C}$

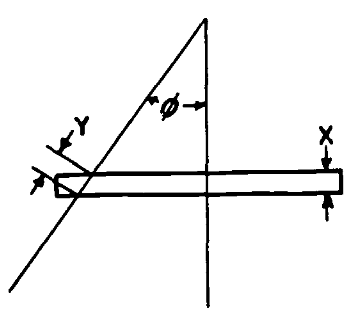
Part III--Answer all questions; show all work clearly. Grade value for each question shown in parenthesis.

(15) 1. Using diagrams show the effect of added filtration on x-ray field distribution (a) parallel to the x-ray tube axis and (b) perpendicular to the x-ray tube axis? Briefly explain the reason for any difference.

Ans.



Added filtration tends to "narrow" the field because of the increasing effective thickness of filter (plane) as you move away from the central beam



$$\cos \phi = \frac{X}{Y}$$

$$Y = \frac{X}{\cos \phi}$$

(20) 2. Aluminum transmission data taken at 100 kVp with two field sizes at the added absorber location were determined to be as follows:

Percent Transmission	2 cm dia. field	4 cm dia. field
	Added absorber--mm Al	
100	0	0
50	1.08	1.10
25	3.40	3.46

a. What are the first and second half-value layers for each field size?

Ans. 2 cm 1HVL = 1.08 mmAl
2 cm 2HVL = 3.40 - 1.08 = 2.32 mmAl
4 cm 1HVL = 1.10 mmAl
4 cm 2HVL = 3.46 - 1.10 = 2.36 mmAl

b. What is the unique first half-value layer?

Ans. Unique 1HVL = 1.08 - (1.10 - 1.08) = 1.06 mmAl

c. What is the unique second half-value layer?

Ans. Unique 2 HVL = 2.32 - (2.36 - 2.32) = 2.28 mmAl

d. What is the unique homogeneity coefficient?

Ans. Unique $H_o = \frac{1.06}{2.28} = 0.465$

e. What is the effective energy of the beam (ρ aluminum = 2.7 g/cm^3) ?

Ans. $\mu/\rho = \frac{0.693}{(HVL)(\rho)} = \frac{0.693}{(0.106)(2.7)} = 2.42\ cm^2/g$

From graph 22.5 keV

(10) 3. At 100 keV, the mass energy transfer coefficient for air is $0.023\ cm^2/g$ and for bone $0.039\ cm^2/g$. Calculate the dose received by the bone if the measured exposure is 10 roentgens.

Ans. $D_b = 0.87 \times \frac{(\mu_{en})_b}{(\mu_{en})_a} = (0.87)(10)\ \frac{(0.039)}{(0.023)} = 14.8\ \text{rad}$

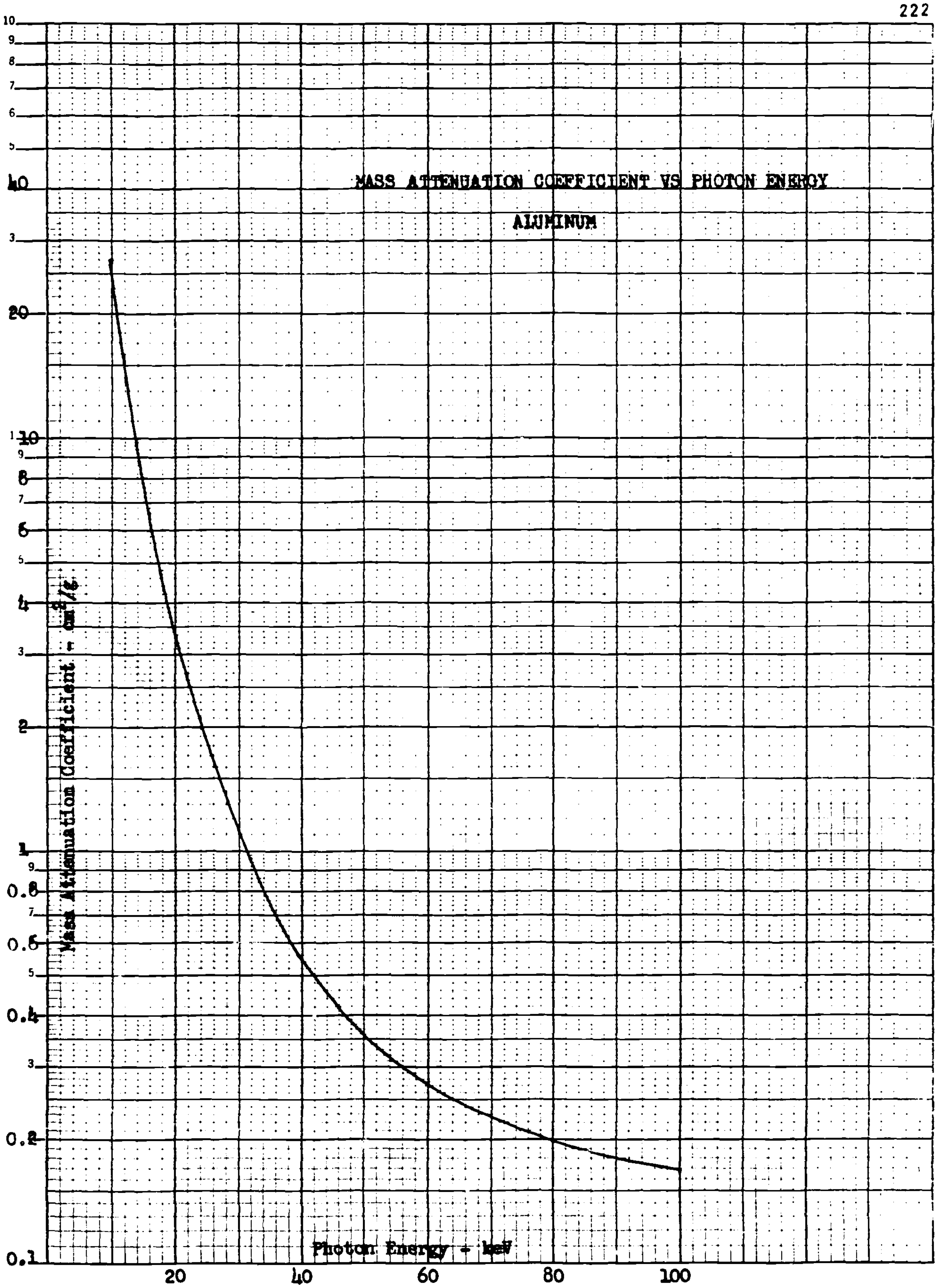
(10) 4. An air equivalent ionization chamber is placed in a muscle tissue and exposed to 100 keV photons. The chamber volume is $1\ cm^3$, the charge collected 1 esu, and the factor f is 0.948. What is the absorbed dose in the tissue?

Ans. $D_m = fX = (0.948)\left(\frac{1\ \text{esu}}{1\ cm^3}\right) = 0.948\ \text{rad}$

(10) 5. An air equivalent ionization chamber is exposed to 100 keV photons and the measured ionization current is 3.33×10^{-12} ampere. If the chamber response at this energy is 3×10^{10} R/amp-min, what is the exposure rate in roentgens per minute?

Ans. $X/t = (3.33 \times 10^{-12}\ \text{amp})\ (3 \times 10^{10}\ \text{R/amp-min}) = 10 \times 10^{-2}$

$= 0.1\ \text{R/min}$


MASS ATTENUATION COEFFICIENT VS PHOTON ENERGY
ALUMINUM
Mass Attenuation Coefficient - cm²/g
Photon Energy - keV
40
20
10
8
6
4
2
1
0.8
0.6
0.4
0.2
0.1
20
40
60
80
100

Appendix A

Equipment List

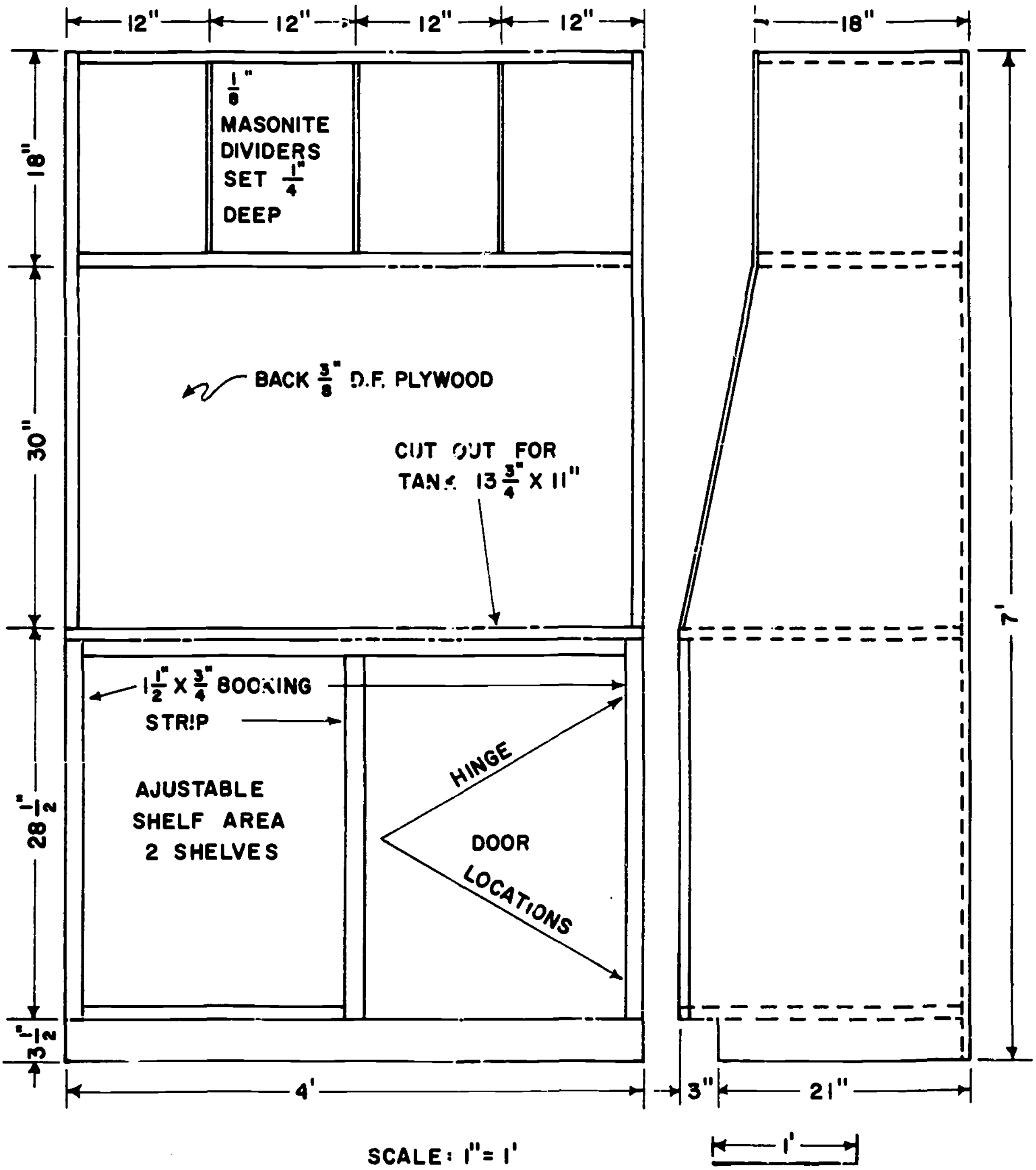
The following is a list of equipment needed for each student laboratory group. Major equipment items would, of course, be used by all laboratory groups. Equipment not generally commercially available and fabricated in the X-Ray Science and Engineering Laboratory and University shops is detailed at the end of this appendix.

Number Required	Item
1	Victoreen model 440 survey meter
1	Victoreen model 444 survey meter
1	Victoreen model 740B survey meter
1	Victoreen model 592B survey meter
1	Victoreen model 570 condenser R-meter
1	Victoreen model 70-5, 25R chamber
1	Victoreen model 687C Minometer II
2	Victoreen model N3A, 0-200mR pocket chambers
1	Bendix model 1200MR, 0-200mR low energy pocket dosimeter
1	Bendix model 906-1 dosimeter charger
1	Victoreen model 555 Radocon II
2	Victoreen model 555-0.1 MA probe
1	Victoreen model 555-0.1 DA probe
2	Ring stands with clamps
1	General Electric Maximar 100 x-ray machine
1	Mercury barometer
1	Mercury thermometer
1	MacBeth model TD-102 densitometer
14	Kodak Personal Monitoring Films, Type 2
1	Kodak model 4L dental film processing hanger
1	Nuclear Data Corp. model ND-A 512 channel analyzer
1	Harshaw 1.5" x 1/4" NaI (Tl) crystal and photomultiplier tube assembly with 0.005" baryllium window and 0.5mm diameter collimeter
1	3M human chest phantom
1	3" Heath Co. d.c. oscilloscope

Number Required	Item
1	Solid state (solar cell) x-ray detector with pre-amplifier (see Figure 462-)
1	Teaching X-Ray Unit, described in USPHS Publication No. 1859.
1	General Electric Co. 90kVp mobile x-ray unit, This unit consists of a G.E. 90kVp dental tube head and control both mounted on a mobile tube stand. The tube head was modified in that the 1.5 mm Al filter built into the head was removed so that the total inherent filtration was equivalent to approximately 1 mm Al and an external filter box and beam defining cone adapter was attached to the threaded dental cone adapter. The filter/adapter assembly accomodates the Maximar 100 filters and cones. Control modifications included the following: a. The stabilized 10 and 15 mA tube current selection was replaced with a continuously variable 0.5-6 mA tube current control. A 0.6 mA tube current meter was included in the control panel (see c below). b. The kVp meter was recalibrated to indicate kVp at 1, 3 and 5 mA tube current. c. The electronic timer and its control switch was removed. The mA meter (a above) was installed in the control at the location of the timer control switch d. Two symchronous motor driven timers were mounted on top of the control panel. One provided time control from 1 second to 55 minutes in one second intervals and the other time control from 1/10 second to 10 seconds in 1/10 second intervals.
1	X-ray film processing station. This is a self-contained film developing station including a dental processing tank (containing one gallon tanks for developer and fixer as well as the wash tank), counter space, and shelf space for film cassettes and film hangers. The tanks will accomodate film up to 8 x 10 inches. Drawings of the station are shown in Figures 462-5 and 462-55.

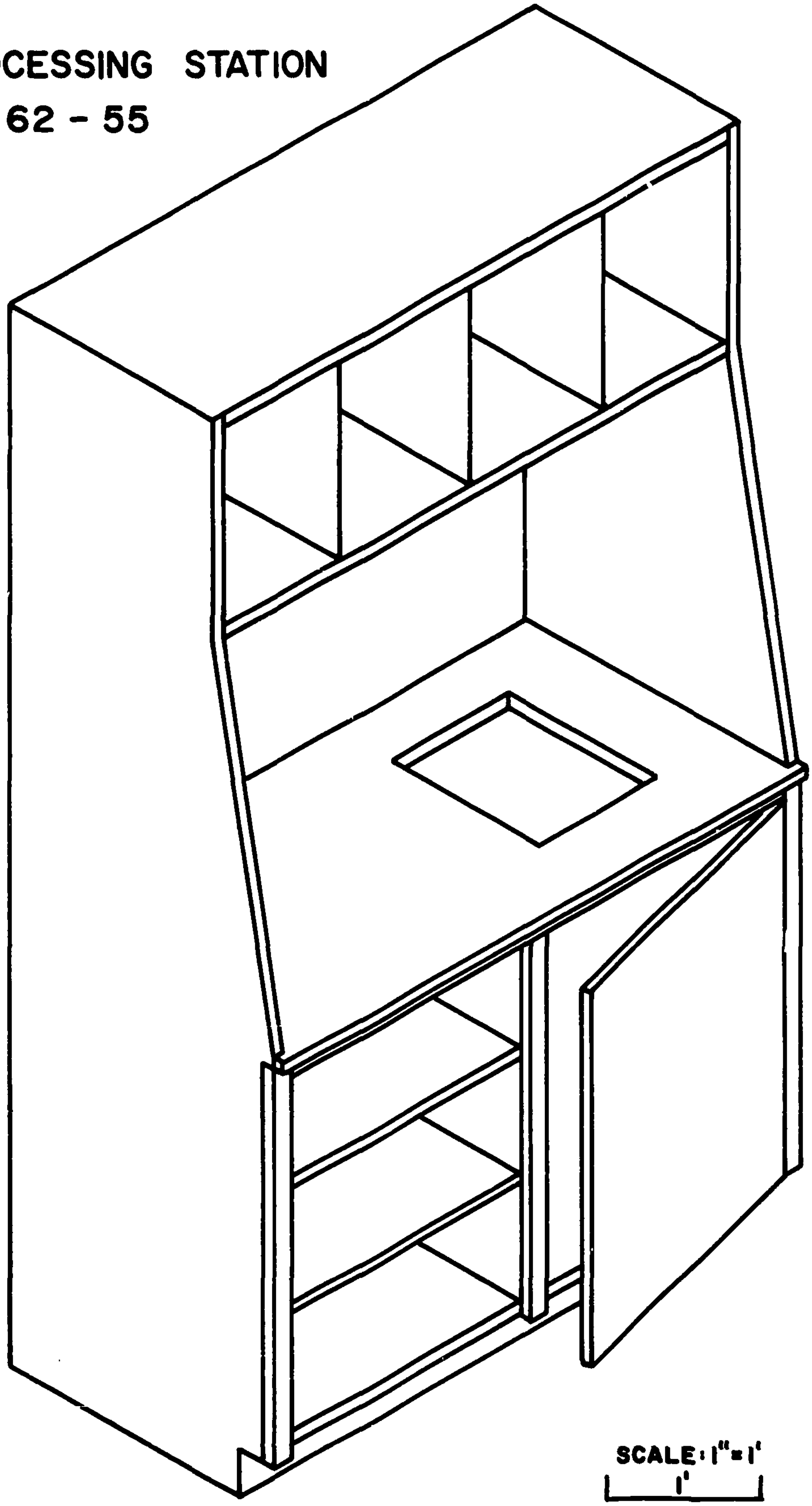
FILM PROCESSING STATION
FIGURE 462-54

ALL MATERIAL $\frac{3}{4}$" D.F. PLYWOOD
UNLESS OTHERWISE SPECIFIED



SCALE: 1"= 1'

FILM PROCESSING STATION
FIGURE 462 - 55



Appendix B

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